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Leaky Coaxial Cable Sensor Studies

by Charles R. Malone, Larry N. Lynch, Lenford N. Godwin

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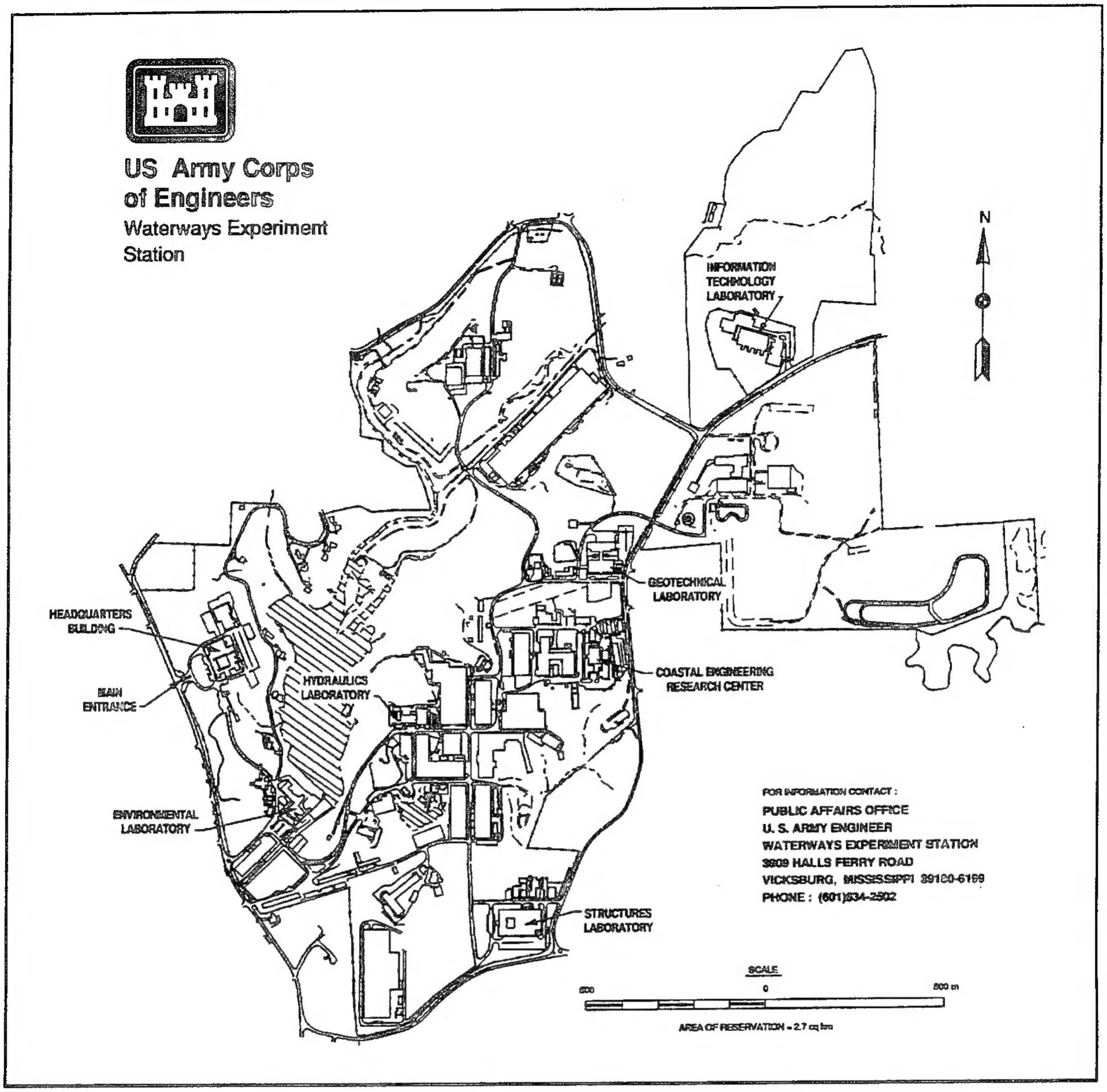

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Contents

Preface

The studies reported herein were conducted by the U.S. Army Engineer Waterways Experiment Station (WES) and were sponsored by the Electronic Security and Communications Center of Excellence, Hanscom Air Force Base, MA.

Work related to the test and evaluation of the TR1 cable was conducted during Fiscal Year 1994 under the general supervision of Mr. Bryant Mather, Director of the Structures Laboratory (SL), WES, and Dr. Jimmy P. Balsara, Chief of the Structural Mechanics Division (SMD), SL, and under the direct supervision of Mr. Gayle E. Albrittion, Chief of the Structural Evaluation Group (SEG), SMD. Mr. Charles R. Malone conducted the study and prepared Chapter 2 of this report.

Work related to the sealant and slot configuration evaluation was conducted during Fiscal Years 1993-1994 under the general supervision of Dr. William F. Marcuson III, Director of the Geotechnical Laboratory (GL), WES, and Dr. George M. Hammitt II, Chief of the Pavement Systems Division (PSD), GL, and under the direct supervision of Mr. Timothy W. Vollor, Chief of the Materials Research and Construction Technology Branch (MRCTB), PSD. Messrs. Larry N. Lynch and L. N. Godwin conducted the study and prepared Chapter 3 of this report.

Dr. Robert W. Whalin was Director of WES during the conduct of these studies and preparation of this report. COL Bruce K. Howard, EN, was Commander.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]
inches	25.4	millimetres
inches per inch per fahrenheit degree	9/5	centimetre per centimetre per celsius degree
pounds (force)	4.448222	newtons
pounds (force) per square inch	6.894757	kilopascals
square inches	6.4516	square centimetres

[1] To obtain Celsius (C) temperature readings from fahrenheit (F) readings, use the following formula: $C = (5/9)(F-32)$. To obtain kelvin readings, use $K = (5/9)(F-32) + 273.15$.

1 Introduction

Leaky Coaxial Cable Sensor Technology Overview

Leaky Coaxial Cable Sensor (LCCS) systems have been used for several years by military organizations, government agencies, and private industries to detect unauthorized entry along the perimeters of high-value assets. LCCS systems typically consist of two cables which encircle a site perimeter and connect to a processor. Deploying the cables consists of either burying the cables 230 mm deep in soil or placing the cables in slots cut in a paved surface. In both soil and pavement, the two cables are placed 1.5 m apart.

LCCS cables are coaxial cables with periodic ports in the outer conductor. These ports allow radio frequency energy to "leak" from one cable (the transmit cable) and couple into the other (the receive cable). Detection of a target occurs when the electromagnetic field above the two cables is disturbed beyond a predefined alarm threshold value.

Purpose and Scope

Two separate but related studies are reported herein. One study involved testing and evaluating the newly developed TR1 sensor cable. Chapter 2 of this report describes the field tests and analyses that were conducted to determine basic performance characteristics of the TR1 sensor cable. The other study involved testing and evaluating new sealant materials and a new slot configuration which offered potential savings in the time and cost of installing LCCS cables in pavement. Chapter 3 of this report describes laboratory tests and analyses that were conducted to measure various chemical, physical, and mechanical properties of the new sealant materials and slot configuration.

2 Test and Evaluation of the TR1 Sensor Cable

Background

Recent technological developments by Senstar Corporation have led to their initial production of the TR1 sensor cable. The "Siamese" TR1 cable consists of two leaky coaxial sensor cables housed in a single jacket as illustrated in Figure 1. Figure 2 compares typical deployment configurations for traditional two-cable sensors and the new TR1 sensor cable.

An obvious advantage offered by the TR1 cable is ease of installation compared to traditional two-cable sensors. The TR1 cable requires only one trench (in soil) or slot (in pavement) whereas traditional two-cable sensors require two parallel trenches or slots. The potential savings in cable installation costs, which have always been a significant percentage of total LCCS system installation cost, makes the TR1 cable an attractive alternative to traditional two-cable sensors.

Purpose and Scope

Before the TR1 cable could be given further consideration for deployment at high-security military sites, certain fundamental questions about the performance characteristics of the cable had to be answered. These questions are listed as follows:

a. What effect does the deployment medium (electrical properties, in particular) have on the target sensitivity of the TR1 cable?

b. What effect does the cable burial depth have on the target sensitivity of the TR1 cable?

c. What are the width and height of the TR1 cable detection field?

d. What effect does target speed (walking versus running) have on the detection capability of the TR1 cable?

e. Can the TR1 cable meet established invalid alarm rate criteria?

f. What weather conditions affect the performance of the TR1 cable?

g. How do the target detection characteristics of the TR1 cable compare with those of the Short Ported Coaxial Sensor (SPCS) cable?

h. When used with the TR1 cable, how does the performance of the Panther 2000 processor compare with that of the TM3-3T processor?

i. How will the TR1 cable perform when deployed on the surface?

The purpose of the study reported in this chapter was to answer the nine questions listed above. Field tests designed to collect data necessary to answer these questions were conducted during the period November 1993 to April 1994. Description of these tests along with results and data analysis are presented in the following paragraphs. Overall conclusions and recommendations are presented at the end of this chapter.

Test Sites

General

Two sites were used for field testing during this study. One was an established intrusion detection systems test site located within the WES reservation boundaries. The other, leased by WES primarily for explosive tests, was located along the Big Black River in southeastern Warren County, Mississippi. For the remainder of this report, these sites will be referred to as "WES site" and "Big Black Test Site (BBTS)".

Figures 3 and 4 illustrate the layout of the WES site and the BBTS, respectively. Polyvinyl chloride (PVC) pipes were buried at each site to facilitate deployment and recovery of the sensor cables. A slot, 14 mm wide and 44 mm deep, was cut along the middle of the concrete slab at the BBTS to allow deployment of the TR1 cable. The cable was pushed to the bottom of the slot and covered with backer rod.

Soil/Pavement

Though each site featured relatively flat, grass-covered terrain, the soil at the two sites was notably different. Laboratory testing was conducted to measure the physical and electrical properties of representative soil samples from each site. Physical properties measurements included grain size distribution and Atterberg limits (liquid and plastic limits). Results of these two tests allowed each sample to be classified according to the Unified Soil Classification System (USCS). Electrical properties measurements included conductivity and dielectric constant, both of which were measured over a range of moisture conditions at a frequency of 60 MHz.

Results of physical properties testing of the WES soil sample and the BBTS soil sample are presented in Figures 5 and 6, respectively. Comments regarding these results are as follows:

a. Both of the soil samples were made up predominantly of fine particles (particles passing the 75-mm (No. 200) sieve). The WES soil contained 97 percent fines and the BBTS soil contained 73 percent fines.

b. The plasticity of the two soil samples was notably different. The liquid limit and plastic limit of the WES soil were determined to be 39 and 25, respectively. The BBTS soil, on the other hand, was found to be non-plastic.

c. The USCS classification of the WES soil sample was "CL", a silty clay. The USCS classification of the BBTS soil sample was "ML", a sandy silt.

Conductivity and dielectric constant data measured in the laboratory are presented in Figures 7 and 8, respectively. (Equipment used to measure soil electrical properties is described in the next section of this report.) Comments regarding these test results are as follows:

a. The conductivity of the two soil samples was considerably different, especially at higher moisture contents. At 20 percent moisture, the conductivity values of the WES soil and BBTS soil were 81 mmhos/m and 50 mmhos/m, respectively.

b. The dielectric constant of the two soil samples was very similar over the entire range of moisture contents. At 20 percent moisture, the dielectric constant was 18 for both the WES soil and the BBTS soil.

A portland-cement concrete slab, shown in Figure 9, was poured at the BBTS for this study. The slab, poured directly on top of the BBTS soil, was 3 m wide, 20 m long and 100 mm thick. No steel reinforcing was placed in the slab. Though the electrical properties of this slab were not measured, measurements made in the past by WES personnel indicated a conductivity value of 20 mmhos/m and a dielectric constant value of 12 for fully cured portland-cement concrete. These values were found to vary little as water was added to the cured concrete.

Test Equipment

General

The block diagram presented as Figure 10 illustrates the basic function and interconnection of each piece of test equipment used during this study. The following paragraphs describe each component in detail.

Sensor cables

Two types of sensor cables were tested during this study, each manufactured by Senstar Corporation of Kanata, Ontario, Canada. The primary cable tested was the TR1 cable, known previously during its development as the Dual Magnetic Slow Attenuating (DMSA) cable. Senstar changed the name of the cable from DMSA to TR1 once the product was introduced on the commercial market. The other cable tested was the Short Ported Coaxial Sensor (SPCS) cable, a traditional two-cable sensor which has been used by the U.S. Air Force for the past several years. The SPCS cable was included in this study for the sake of comparison with the TR1 cable. A photo of the two cables is presented in Figure 11. Schematics of the two cables are presented in Figure 12.

During the course of this study, two separate TR1 cables were used. One of the TR1 cables, referred to as the long TR1 cable, consisted of 25 m of inactive lead-in cable, 100 m of active cable, a pair of decouplers, and 4 m of inactive termination cable. The other TR1 cable, referred to as the short TR1 cable, consisted of 25 m of inactive lead-in cable, 22 m of active cable, a pair of decouplers and 4 m of inactive termination cable.

Only one SPCS cable (pair) was used during this study. This cable consisted of 25 m of inactive lead-in cable, 22 m of active cable, a pair of decouplers and 4 m of inactive termination cable.

Sensor processors

The primary processor used during this study was the Panther 2000 manufactured by Senstar Corporation. During one test, the TM3-3T processor (companion processor for the SPCS cable) was also used for the sake of comparison with the Panther 2000. Except for this one comparative test, all sensor performance data collected during this study was collected from the Panther 2000. A photo of the Panther 2000 and TM3-3T is presented in Figure 13.

Notable features of the Panther 2000 are summarized as follows:

a. Indoor mounting. The unit is not weatherproof.

b. Three user selectable operating frequencies (40.665, 40.680 and 40.695 MHz).

c. User-adjustable sensitivity (0-100).

d. Output via analog display meter (included with the processor) or hardwire to user-supplied display/recording device.

Data acquisition system

The data acquisition system used to display and record output from the sensor processor consisted of a 386-based personal computer (PC) with the following features:

a. *External terminal board.*

b. *Analog-to-digital (A/D) board.*

c. *60 Mbyte hard drive.*

d. *VGA monitor.*

e. *Labtech Notebook software.*

The analog signal from the sensor processor was transmitted to the terminal board via an RG-58 coaxial cable. The analog signal was then transmitted via a 50-wire ribbon cable from the terminal board to the A/D board where it was converted to a digital signal at the rate of 4 samples per second. The Labtech Notebook software allowed the digital signal to be concurrently displayed to the VGA monitor and recorded to the hard drive in units of decibels (dB).

Video equipment

Equipment used to record and display visual imagery during invalid alarm rate (IAR) testing included the following:

a. *Closed Circuit Television (CCTV) Cameras.* Cameras were mounted on tripods and positioned to provide 100 percent coverage of the cable being tested. Two cameras were used at the BBTS and one was used at the WES site. Since supplemental lighting was not used at either site, camera images were clear only during normal daylight hours.

b. *Video Cassette Recorders (VCR's).* Camera signals were transmitted to time-lapse VCR's via RG-59 coaxial cable. Two VCR's were used at the BBTS and one was used at the WES site.

c. *Monitors.* Output from the VCR's was transmitted to black and white monitors via RG-59 coaxial cable. Two monitors were used at the BBTS and one was used at the WES site.

Weather station

The portable weather station used during this study, shown in Figure 14, was capable of measuring and recording rainfall, wind speed, wind direction, air temperature, solar radiation, barometric pressure and relative humidity.

Dielectric constant and conductivity (DICON) probe

The WES-developed DICON probe, illustrated in Figure 15, was used to measure the dielectric constant and conductivity of the soil at a frequency of 60 MHz. The DICON probe actually consisted of two components, the probe and the reflectometer, connected via an RG-58 coaxial cable. To make soil measurements in the field, the probe was inserted into the ground as shown in Figure 16. Measurement depths for this study were 100, 200, and 300 mm. A specially modified probe which did not include the steel pipe assembly was used to measure electrical properties of soil samples in the laboratory.

Test Procedures

General

In order to collect realistic and repeatable test data, certain standard test procedures were followed for every test conducted during this study. These standard procedures related to the test target and cable calibration are described below.

Test target

Two adult males, each approximately 1.7 m tall and 70 kg, were selected as test targets for this study. The purpose of these test targets was to impart controlled, repeatable stimuli to the detection field above the sensor cable. The standard stimulus used during every test to measure target sensitivity was a crosswalk. A crosswalk consisted of the target walking at a normal pace (approximately 1.25 m/s) across the detection field. The target began the crosswalk approximately 2 m outside the edge of the detection field and proceeded in a direction perpendicular to the sensor cable(s) until he was approximately 2 m beyond the other edge of the detection field. Other stimuli used for specific tests will be described in subsequent paragraphs.

Cable calibration

The first step in calibrating the cable was recording the response of the cable to a series of crosswalks. One crosswalk was done every 2 m along the entire length of the active cable. After the crosswalks were completed, the magnitudes (in dB) of the crosswalks were reviewed. The sensitivity of the processor was then adjusted so that the minimum crosswalk magnitude would be approximately 10 dB above threshold. This calibration procedure was thought to provide a reasonable balance between target detection and invalid alarm rejection.

Effect of Deployment Media

Test procedure

The objective of this test was to obtain quantitative data relating the target sensitivity of the TR1 cable to the electrical properties of the cable deployment medium. This objective was achieved by following the steps described below:

a. *Deploy TR1 cable.* The short TR1 cable was deployed in three successive media - WES soil, BBTS soil and pavement. Steps b-d below were followed for each cable deployment.

b. *Calibrate TR1 cable.* The processor sensitivity was set at 66 (WES soil), 50 (BBTS soil) and 47 (pavement).

c. *Record response of TR1 cable to multiple crosswalks.* Crosswalks were done twice every meter along the active TR1 cable.

d. *Measure soil electrical properties.* Locations where the crosswalk magnitudes were low, average, and high were selected for conductivity and dielectric constant measurements. At each of the three selected locations the DICON probe was used to make conductivity and dielectric constant measurement at depths of 100, 200, and 300 mm.

Results and analysis

Crosswalk data and soil electrical properties data obtained during this test are presented graphically in Figures 17 and 18, respectively. Relevant observations regarding these results are presented in the following paragraphs.

The crosswalk magnitudes shown in Figure 17 all reflect the processor sensitivity setting used for the WES soil. To facilitate comparison of data, the actual magnitudes recorded for the BBTS soil and pavement were adjusted according to the following equation:

$$M_{Adj} = M + (S_{WES} - S)/1.85$$

where

M_{Adj} = Adjusted crosswalk magnitude for BBTS soil or pavement, in dB

M = Actual crosswalk magnitude for BBTS soil or pavement, in dB

S_{WES} = Processor sensitivity setting for WES soil = 66

S = Processor sensitivity setting for BBTS soil or pavement

The effect of deployment media on TR1 target sensitivity is best illustrated by comparing test data from the WES soil with test data from the BBTS soil. Comparing these two sets of data clearly shows that the lower electrical properties of the BBTS soil provided a higher TR1 target sensitivity. On average, the crosswalk magnitudes for the TR1 cable in BBTS soil were 7 dB higher than those for the TR1 cable in WES soil. The average conductivity of the BBTS soil was 28 mmhos/m compared with 74 mmhos/m for the WES soil. The average dielectric constant of the BBTS soil was 26 compared with 37 for the WES soil.

The TR1 cable deployed in pavement slots provided only slightly higher target sensitivity (on average, less than 1 dB) than did the TR1 cable deployed in the BBTS soil. This slight difference in target sensitivity reflects the combined effects of the electrical properties of the deployment media (roughly the same for the pavement and BBTS soil) and the depth of the cable (44 mm in pavement, 230 mm in BBTS soil). The effect of burial depth will be discussed in the next section of this report.

Data collected during this test clearly indicate an inverse relationship between the electrical properties of the burial medium and the target sensitivity of the TR1 cable. Practical implications of this finding related to operational deployment and performance of TR1 cable are listed as follows:

a. When deployed in soils exhibiting very high electrical properties, the detection field of the TR1 cable may be attenuated to the point of providing unreliable target detection, even when the processor is set at maximum sensitivity. In this scenario, the dynamic range of the TR1 cable and associated processor has been exceeded. The exact soil electrical properties values which would cause the dynamic range of the TR1 cable to be exceeded cannot be determined exactly from the results of this study. A conservative estimate, however, is that the TR1 cable would perform satisfactorily in soils exhibiting conductivity values up to 140 mmhos/m. This would include the majority of naturally occurring soils.

b. Changes in soil electrical properties resulting from changes in soil state (unfrozen to frozen, wet to dry) will change the target sensitivity of the TR1 cable. In general, higher electrical properties are associated with wet, unfrozen soil, and lower electrical properties are associated with dry, frozen soil. Operational maintenance personnel should be aware of changes in target sensitivity and the subsequent need to recalibrate the TR1 cable during seasonal changes in the weather pattern.

c. Deployment media transitions (sandy soil to clay soil, soil to pavement, etc.) within a single TR1 cable run will cause non-uniform target sensitivity along that cable. Consequently, media transitions should be minimized to the greatest extent possible when planning the TR1 cable route at an operational site.

Effect of Cable Burial Depth

Test procedure

A test was conducted at the WES site to quantitatively assess the effect of cable burial depth on the target sensitivity of the TR1 cable. This test involved the following sequence of steps:

a. *Deploy TR1 cable at 230-mm depth and calibrate.* The short TR1 cable was placed in a PVC pipe buried 230 mm below the surface. The processor sensitivity was set at 66.

b. *Record response of TR1 cable to multiple crosswalks.* Crosswalks were done twice every metre along the active TR1 cable.

c. *Deploy cable at 80-mm depth.* The TR1 cable was removed from the 230-mm-deep pipe and placed in a pipe buried 80 mm below the surface. The 80-mm-deep pipe was directly above the 230-mm-deep pipe. The cable was not recalibrated, and, consequently, the processor sensitivity was left at 66.

d. *Record response of TR1 cable to multiple crosswalks.* As in step b, crosswalks were done twice every meter along the active TR1 cable.

Results and analysis

Results of this test are presented graphically in Figure 19. This graph clearly shows the increase in target sensitivity caused by raising the cable from 230 to 80 mm. On average, raising the cable increased the crosswalk magnitude by 5 dB. Note, however, that the effect of raising the cable is much more pronounced for the first 13 m of the cable run (average increase in crosswalk magnitude = 7 dB) than it is for the last 9 m (average increase in crosswalk magnitude = 3 dB). This suggests that the effect of raising the cable is not sustained for more than a few meters.

The primary implication of these test results related to operational cable deployment is that changing the cable burial depth can be used to "fine tune" the detection sensitivity along a given cable run. This technique, long used for traditional two-cable sensors, can be used during the cable installation process to "tune up" a localized low-sensitivity area (by raising the cable) or to "tune down" a localized high-sensitivity area (by lowering the cable). Burying the cable at a shallow depth should not, however, be expected to produce a sustained increase in target sensitivity over a long cable run.

Detection Field Width

Test procedure

The purpose of this test was to collect data necessary to determine the width of the detection field formed by the TR1 cable. The following sequence of steps were followed during this test:

a. *Deploy TR1 cable.* The short TR1 cable was deployed in 3 successive media -- WES soil, BBTS soil, and pavement. Steps b through e below were followed for each cable deployment.

b. *Calibrate TR1 cable.* The processor sensitivity was set at 66 (WES soil), 50 (BBTS soil), and 47 (pavement).

c. *Record response of TR1 cable to multiple crosswalks.* Crosswalks were done twice every meter along the active TR1 cable.

d. *Select locations along the active TR1 cable representative of low, medium and high target sensitivity.* These three locations were selected by examining crosswalk data.

e. *Measure detection field width and crosswalk magnitude at each selected location.* The technique to measure detection field width, illustrated in Figure 20, involved the test target shuffling at a very slow pace (approximately 0.25 m/s) toward the cable until the processor issued an alarm. Immediately upon hearing the alarm, the target stopped and the distance from his forward ankle to the cable was measured. This sequence was followed a total of four times from each direction at each location. Four crosswalks were also conducted at each location.

Results and analysis

Results of this test are presented graphically in Figure 21. Note that of the nine data points shown on this graph, 3 were collected from each of the 3 cable deployments. Detection field width values ranged from 0.8 to 2.1 m. The correlation between detection field width and crosswalk magnitude as described by the equation of the best fit curve was good. The equation is:

$$W = 1.2\,ln(M) - 1.35$$

where

W = detection field width, in metres
M = crosswalk magnitude, in dB

The chief implication of these test results related to operational TR1 cable performance is stated as follows: If a TR1 cable is calibrated so that crosswalk magnitudes along the length of the cable vary from a low of 10 dB to a

high of 20 dB, the detection field can be expected to be between 1.4 and 2.2 m wide.

Detection Field Height

Test procedure

The purpose of this test was to collect data necessary to determine the height of the detection field formed by the TR1 cable. This test was conducted in conjunction with the detection field width test; therefore, steps a-d were identical for both tests. The steps listed below were followed to measure detection field height:

a. *Deploy TR1 cable.*

b. *Calibrate TR1 cable.*

c. *Record response of TR1 cable to multiple crosswalks.*

d. *Select locations along the active TR1 cable representative of low, medium and high target sensitivity.*

e. *Measure crosswalk magnitude at 4 different heights at each selected location.* The four heights were 0 m (ground surface), 0.13 m, 0.25 m and 0.38 m. These different heights were achieved by using a 0.5 m by 2.5 m wooden platform supported by varying numbers of bricks and wood blocks at the corners. This platform is shown in Figure 22. Four crosswalks were conducted at each height.

Results and analysis

Results of this test are presented graphically in Figure 23. Note that each of the nine curves shown on this graph represents a specific location along one of the three TR1 cable deployments. Note also that each curve is formed by connecting four individual data points, each representing a specific height above the ground surface.

In examining these nine curves, two things are apparent. First, each curve is approximately linear. Second, the slope of the curves is very similar. Considering these two factors, a best fit line was calculated for each set of four data points and the slopes of these nine best fit lines were averaged. The average slope of the best fit lines, -25.1 dB/m, is thought to be a good approximation for the rate of decrease in target sensitivity as a function of height above the ground surface.

The chief implication of these test results related to operational TR1 cable performance is stated as follows: If a TR1 cable is calibrated so that cross-

walk magnitudes along the length of the cable vary from a low of 10 dB to a high of 20 dB, the detection field can be expected to be between 0.4 and 0.8 m high.

Effect of Target Speed

Test procedure

The purpose of this test was to collect data necessary to establish a quantitative relationship between crossrun magnitude and crosswalk magnitude for the TR1 cable. This test was conducted in conjunction with the detection field width and height tests, therefore, steps a-d were identical for all three tests. The steps listed below were followed to measure crossrun and crosswalk magnitudes:

a. *Deploy TR1 cable.*

b. *Calibrate TR1 cable.*

c. *Record response of TR1 cable to multiple crosswalks.*

d. *Select locations along the active TR1 cable representative of low, medium and high target sensitivity.*

e. *Measure crosswalk magnitude at each selected location.* Four crosswalks, two from each direction, were done at each location.

f. *Measure crossrun magnitude at each selected location.* The speed of the runs (approximately 2.7 m/s) was more a jog than a sprint. Four crossruns, two from each direction, were done at each location.

Results and analysis

Results of this test are presented graphically in Figure 24. The nine data points collected during this test are included on the graph along with a best fit line. The functional relationship between crossrun magnitude and crosswalk magnitude is specified by the equation of the best fit line:

$$M_R = 0.92M_W - 1.66$$

where

M_R = crossrun magnitude, in dB
M_W = crosswalk magnitude, in dB

The chief implication of these test results related to operational TR1 cable performance is that the TR1 cable is sensitive to target speed. In quantitative terms, the TR1 cable will be 2-3 dB less sensitive to a running intrusion (2.7 m/s) than it will be to a walking intrusion (1.25 m/s).

Invalid Alarm Rate

Test procedure

The purpose of this test was to obtain data necessary to assess the invalid alarm rate of the TR1 cable. This purpose was achieved by following the steps listed below:

a. *Deploy the long TR1 cable at the BBTS.* The cable was deployed in a "U" configuration as shown in Figure 4. The first 36 m were buried 230 mm deep in soil, the next 20 m were placed in slots in the pavement and the last 44 m were buried 80 mm deep in soil.

b. *Calibrate TR1 cable.* The processor sensitivity was set at 53.

c. *Record response of TR1 cable to multiple crosswalks.* Two crosswalks were conducted every 2 m along the active cable.

d. *Record processor output, video imagery and weather data over a 72-hr period.*

e. *Remove the long TR1 cable from the BBTS and redeploy it at the WES site.* The cable was deployed at the WES site in a PVC pipe buried 230 mm deep in a linear configuration.

f. *Repeat steps b-d.* The processor sensitivity was set at 62 at the WES site.

Results and analysis

Results of the BBTS portion of this test are presented graphically in Figures 25 and 26. After the cable was calibrated, most of the crosswalk magnitudes were between 10 and 20 dB, as illustrated in Figure 25. Note, however, the significant variation in target sensitivity among the three deployment configurations. The graph in Figure 26 indicates that, during the 72-hr monitoring period, the processor output exceeded the alarm threshold on 7 separate occasions. Five of the seven occasions occurred during a thunderstorm, the specific effects of which will be discussed in the next section of this report. Examination of the video tapes and the weather data produced no explanation for the other two occasions when the alarm threshold was exceeded.

Results of the WES site portion of this test are presented graphically in Figures 27 and 28. After the cable was calibrated, all of the crosswalk magnitudes were between 10 and 20 dB, as illustrated in Figure 27. Note the relative uniformity of target sensitivity at the WES site compared to that at the BBTS. The graph in Figure 28 indicates that, during the 72-hr monitoring period, the processor output exceeded the alarm threshold on 5 separate

occasions. Examination of the video tapes and weather data produced no explanation for these 5 occasions when the alarm threshold was exceeded.

Excluding the period of thunderstorms at the BBTS, a total of 7 unexplained alarms occurred during the 144 hr of monitoring at the two sites. On average, this computes to 1.2 unexplained alarms per 100 m of active cable per 24 hr. The implication of these test results related to operational performance of the TR1 cable is that an invalid alarm rate of 2 alarms per 100 m sensor zone per 24 hr can be achieved with the TR1 cable.

Weather Effects

Procedure

The data collected during the IAR test described previously were analyzed to determine the effect of weather on TR1 performance. Weather data were compared with processor output data to identify specific weather patterns which produced a significant change in processor output. Trends were identified strictly by observation; i.e., no statistical analysis techniques were employed.

Results and analysis

The only weather pattern found to significantly affect processor output was the thunderstorm which occurred during the BBTS portion of the IAR test. The combined effects of the wind and rain associated with the thunderstorm on processor output are illustrated in the three graphs presented as Figure 29. Note that the processor output and wind speed are actually average values calculated over 5-min periods. Note also that the rainfall accumulation is the accumulation during 5-min periods. The largest increases in processor output occurred just as the thunderstorm began around midnight and during the period of heaviest rainfall around 4:00 am. As the rainfall ended around 9:00 am, both processor output and wind speed increased noticeably. This correlation suggests that wind-induced motion of standing water (puddles) near the cables caused the increase in processor output. Though the BBTS was fairly well drained, certain low spots tended to hold water after a heavy rain.

Implications of these test results related to operational deployment and performance of the TR1 cable are summarized as follows:

a. The TR1 cable route should be well drained to prevent unwanted alarms from standing water. Prior to deploying the cable at a site, areas along the proposed cable route which typically hold water after a rainfall or snow melt should be built up by appropriate grading and/or fill.

b. Unwanted alarms can be produced by the combined action of wind and rain. The frequency of alarms will depend on the intensity of the storm.

TR1/SPCS Cable Comparison

General

The purpose of this test was to collect data comparing the performance characteristics of the TR1 cable and the SPCS cable in three specific areas:

a. *Effect of deployment media on target sensitivity.*

b. *Detection field width.*

c. *Detection field height.*

Data were collected according to procedures described previously in this report. The short (22 m active) TR1 and SPCS cables were used during this test. The first half of this test was conducted at the WES site with the cables deployed in PVC pipes at a depth of 230 mm. The second half of this test was conducted at the BBTS with the cables again deployed in 230-mm-deep PVC pipes. The cables were not deployed in pavement slots for this test.

Effect of deployment media

Crosswalk magnitude data collected at each site for the two cables are presented graphically in Figure 30. Note first that the crosswalk magnitudes shown in Figure 30 all reflect the processor sensitivity setting used for the SPCS cables deployed in WES soil. Data from the other 3 cable deployments were adjusted (as described previously in this report) to facilitate comparison of the four sets of data.

Comparing the performance of the two cables in BBTS soil, it is clear that the average crosswalk magnitude of the SPCS cable was only slightly higher (approximately 2 dB) than that of the TR1 cable. In the WES soil the difference between the average crosswalk magnitudes for the two cables was even less (approximately 1 dB higher for the SPCS cable). The chief implication of this result is that the effect of the electrical properties of the deployment medium on target sensitivity is roughly the same for the two cables.

Detection field width

Detection field width data collected for the TR1 and SPCS cables at the two test sites are presented graphically in Figure 31. A total of 6 data points (3 collected at each test site) along with a best fit curve are plotted for each cable. Calculating the difference between the two best fit curves reveals that the SPCS detection field is approximately 0.5 m wider than that of the TR1 cable.

Detection field height

Detection field height data collected for the TR1 and SPCS cables at the two test sites are presented graphically in Figure 32. A total of 6 curves (3 collected at each test site) are plotted for each cable. Comparing the average slope of the 12 curves reveals that the rate of decrease in target sensitivity as a function of height above the ground surface was roughly the same for the two cables. This result implies that if a TR1 cable and an SPCS cable are calibrated according to the same procedure, there will be no difference between the average height of the two detection fields.

Panther 2000/TM3-3T Processor Comparison

Procedure

The following steps were followed to collect data necessary to compare the performance of the Panther 2000 and TM3-3T processors:

a. *Deploy long TR1 cable.* The cable was deployed in a "U" configuration at the BBTS as described previously in this report.

b. *Connect TR1 cable to Panther 2000 processor and calibrate.* The processor sensitivity was set at 53.

c. *Record response of TR1 cable to multiple crosswalks.* Two crosswalks were conducted every 2 m along the active cable.

d. *Connect TR1 cable to TM3-3T processor and calibrate.* The processor threshold was set at 34 dB.

e. *Record response of TR1 cable to multiple crosswalks.*

Results and analysis

Results of this test are presented graphically in Figure 33. Note that the target sensitivity provided by the two processors is very similar at every crosswalk location along the active TR1 cable. This indicates that the same target sensitivity will be provided regardless of whether the Panther 2000 or TM3-3T is used with the TR1 cable.

Performance of Surface-Laid Cables

Procedure

The purpose of this test was to evaluate the performance of the TR1 cable when deployed on the surface. Data for this test were collected according to the following procedure:

a. *Deploy the long TR1 cable on the surface at the BBTS.* The "U" shaped cable path included both soil and pavement as illustrated in Figure 4. Plastic cable ties were used to anchor the cable to wooden stakes driven in the soil as shown in Figure 34. Sandbags were used to stabilize the cable on the pavement surface as shown in Figure 35.

b. *Calibrate the TR1 cable.* The processor sensitivity was set at 43.

c. *Record response of TR1 cable to multiple crosswalks.* Two crosswalks were conducted every 2 m along the active cable.

d. *Record processor output, video imagery and weather data over a 72-hr period.*

Results and analysis

Crosswalk magnitude data are presented graphically in Figure 36. All but one of the data points were between 10 and 20 dB, indicating fairly uniform sensitivity along the length of the cable. This is an important point because one of the main reasons that traditional two-cable systems have not been used on the surface is nonuniform target sensitivity along the cable path. It appears that the design of the TR1 cable has significantly reduced this problem.

Data collected during the 72-hr monitoring period are presented graphically in Figure 37. Of particular note here are the many occasions when the processor output exceeded the alarm threshold. Examination of the video tape revealed that a few of the alarms were generated by crows walking over the cable. The period of excessive alarms around noon on 10 December coincided with a period of intermittent rain showers.

One of the more interesting correlations is illustrated in Figure 38. The three graphs here indicate that both solar radiation and wind speed had an effect on the average background signal from the cable. Note particularly the corresponding cycle of increasing/decreasing processor output, solar radiation and wind speed during 11 December. The main implication of these correlations is that the thermal and mechanical instability inherent to a surface deployment were prime contributors to the problem of excessive invalid alarms.

Results of this test indicate that the overall performance of surface-laid TR1 cables will not be as good as the performance of cables buried in soil or installed in pavement slots. Though a TR1 cable deployed on the surface and calibrated in the manner used during this study will provide good detection, an invalid alarm rate of 2 alarms per 100 m zone per 24 hr will be difficult to achieve. If, however, a surface-laid cable is calibrated so that the minimum crosswalk magnitude for a given cable run is only 2 or 3 dB above alarm threshold, an acceptable IAR can probably be achieved. It must be understood that a cable calibrated in this fashion will provide reliable detection only for casual, low-threat intrusions.

Conclusions

Results of this test and evaluation effort lead to the following conclusions regarding the performance of the TR1 cable:

a. TR1 target sensitivity is inversely related to the electrical properties of the deployment medium. On average, target sensitivity was 7 dB higher in the BBTS soil (conductivity = 28 mmhos/m, dielectric constant = 26) than it was in the WES soil (conductivity = 74 mmhos/m, dielectric constant = 37).

b. TR1 target sensitivity is inversely related to cable burial depth. On average, target sensitivity was 5 dB higher for the 80 mm burial depth than it was for the 230 mm burial depth. Results seemed to suggest, however, that this may be a localized effect that diminishes after a few meters.

c. When properly calibrated, the TR1 cable will provide a detection field that is between 1.4 and 2.2 m wide and between 0.4 and 0.8 m high.

d. TR1 target sensitivity is inversely proportional to target speed. On average, the response of the TR1 cable was 2 to 3 dB lower for a running (2.7 m/s) target than it was for a walking (1.25 m/s) target.

e. An IAR of 2 alarms per 100 m zone per 24 hr is achievable with the TR1 cable.

f. The combined effects of rain, surface water and wind will generate alarms for the TR1 cable.

g. The effect of burial medium electrical properties on target sensitivity is roughly the same for the TR1 and SPCS cables.

h. The SPCS detection field is approximately 0.5 m wider than the TR1 detection field.

i. There is no difference in the height of the detection fields provided by the SPCS and TR1 cables.

j. When used with the TR1 cable, there is no apparent difference in the target sensitivity provided by the Panther 2000 processor and that provided by the TM3-3T processor.

k. The target sensitivity of TR1 cables deployed on the surface is similar to that of buried cables or cables installed in pavement slots. However, surface-laid cables are inherently more susceptible to invalid alarms because of their mechanical and thermal instability.

Recommendations

Recommendations related to future testing and deployment of the TR1 cable are summarized as follows:

a. Testing should be conducted in a high-loss soil (conductivity > 150 mmhos/m) to further define the relationship between TR1 detection sensitivity and soil electrical properties. Results would establish the dynamic range of the cable with respect to soil conductivity and dielectric constant.

b. Until the dynamic range of the TR1 cable has been established conclusively, the TR1 cable should not be deployed in soils which exhibit conductivity values greater than 140 mmhos/m.

c. The TR1 cable should be deployed only at sites where the detection performance of the TR1 cable is sufficient for the anticipated threat. Comparing the performance data contained in this report with the threat definition for a particular site or asset will allow one to determine whether or not the TR1 cable should be used.

3 Sealant and Slot Configuration Evaluation

Background

The sealant material and slot configuration used to install LCCS cables was selected during evaluations conducted in the early 1980's. Since that time, there have been additional silicone joint sealant materials introduced onto the market and there has been an interest in minimizing the cost of sensor cable installation. Three potential methods of reducing installation cost are:

a. Approve multiple sealant materials for use in sensor cable installation thus allowing the installer to select the most economical material.

b. Reduce the labor associated with the installation of the sealant material, i.e., use self-leveling materials instead of materials that require tooling in the joint.

c. Modify the slot/sealant configuration to reduce the amount of sealant required to seal the slot.

A research investigation was initiated to evaluate new sealant materials and consider slot modification with the main objective of reducing installation costs without adversely affecting the sensor cable performance. The research investigation was separated into two phases. The FY 93 phase included identifying potential alternative sealant materials, evaluating those sealants in the laboratory, and providing recommendations for slot/sealant configuration modifications.

The FY 93 sealant/slot configuration investigation was entitled "Sealant Evaluation for Ported Coaxial Cable Sensor (PCCS)/Short Ported Coaxial Sensor (SPCS) Cable installation." The test plan included identifying joint sealant materials that were commercially available which could be satisfactorily used as an alternate to the Dow Corning® 888 silicone sealant, and to investigate two alternate installation geometries which would require the use of less sealant material in the cable slot. The sealant materials evaluated during this project are provided in Table 1. Allowing alternate

sealant materials to be used should increase competition and will allow the user to select the lowest priced material. The use of less material in the joint would reduce material costs and therefore reduce project costs.

The sealant evaluations conducted in FY 93 included the tests used in the early 1980's which resulted in the selection of Dow Corning® 888 as the only sealant acceptable for the cable installation. The main standard tests were resilience, fuel resistance, compatibility, and buckling. In addition to these standard tests, physical and chemical analysis techniques were used to evaluate the sealants. In the FY 94 evaluations, the evaluations were focused on the material properties of the Will-Seal™ 150 material, physical analysis techniques, and determining the maximum slope on which the self-leveling materials could be used effectively.

Table 1
Sealant Materials Evaluated

Sealant	Generic Description[1]
Dow Corning® 888[2]	A single component, nonsag, low-modulus, moisture cure silicone sealant for use in portland cement concrete (PCC) pavements. It is formulated to offer weathering resistance and remains elastic and rubbery from -80 to 300°F.
Dow Corning® 890[2,3]	A single component, self-leveling, ultra-low modulus, moisture curing silicone sealant for use in PCC and asphalt cement concrete (ACC) pavements. It is formulated to provide a flexible seal which offers weathering resistance and remains elastic and rubbery from -50 to 300°F.
Dow Corning® 9-1224[2]	An experimental single component, nonsag silicone sealant manufactured specifically for cable installation.
Koch Product 9050SL[2]	A single component, self-leveling, low-modulus polysulfide based sealant for use in PCC pavements. The sealant is a moisture cure system which meets the fuel-immersed bond test of Federal Specification SS-S-200E and ASTM D 3569. *This material was removed from the market in mid 1994.*
Crafco RoadSaver Silicone[3]	A single component, nonsag, low-modulus, moisture curing silicone sealant for use in PCC pavements. It is formulated to offer weathering resistance and remains elastic and rubbery to temperatures as low as -50°F.

[1] Information for the general description was taken from manufacturer's literature.
[2] Sealant evaluated during FY 93 project.
[3] Sealant evaluated during FY 94 project.

Table 1 (Concluded)	
Sealant	**Generic Description**[1]
Crafco RoadSaver Silicone SL[3]	A single component, self-leveling, low-modulus, moisture curing silicone sealant for use in PCC pavements. It is formulated to offer weathering resistance and remains elastic and rubbery to temperatures as low as -50°F.
Miles Baysilone 960[3]	A single component, low modulus, moisture curing joint sealant formulated to provide a flexible seal for joints in PCC pavements. Baysilone 960 offers weathering resistance and remains elastic and rubbery in temperatures ranging from -40 to 300°F.
Will-Seal™ 150[3]	An open-cell, polyester polyurethane expanding foam that has been impregnated with neoprene rubber that is suspended in chlorinated hydrocarbons. It will adjust to variations in the joint contour and it must remain in compression to function properly. It is resistant to gasoline, diesel fuels, solvents, salts, and acids. The material will remain functional to temperatures as low as -40°F.

Test Procedures

Sealant standard tests

Each of the standard tests were first used in the "Short Perimeter Intrusion Radar and Ported Coaxial Cable Sensor Slot/Seal Study," as a screening method to select joint sealant materials that were acceptable for use in cable installation. From the original evaluation, Dow Corning® 888 silicone sealant was selected; therefore, for a sealant material to be an acceptable alternate it must exhibit similar properties to the Dow Corning® 888 or a justification given for the decrease in the test requirement.

Compatibility test

The compatibility testing was conducted to ensure that the sealant material would not be adversely affected when used in asphalt cement concrete (ACC) pavements or when used in conjunction with other potential alternate sealants. The compatibility with the ACC pavement is a concern because many of the silicone sealants are not recommended for use in ACC pavements. The compatibility with other potential alternate sealants is important because during repair activities, two different types of sealants may be used.

The ACC pavement compatibility test used for this study was taken from Federal Specification SS-S-1401C which was developed for non-jet-fuel-resistant, hot-applied sealants. The test requires that the sealant material be placed into a slot that has been cut into an asphalt pavement core and allowed to cure. The asphalt core/sealant is then placed in an oven set at 140°F for

168 hr. After conditioning, the core is removed from the oven and a visual inspection of the sealant/asphalt interface is made. Specifically, the sealant/asphalt interface is examined to determine if a chemical reaction has occurred that caused the sealant to revert back to a liquid. If the sealant does not revert to a liquid, exhibit an adhesion failure, or adversely affect the asphalt concrete, the material is rated as satisfactory. The results of the ACC pavement compatibility testing are provided in Table 2.

The compatibility between the different sealant materials was evaluated by placing a 1/4 in. thick bead of material on a glass plate. A 1/4 in. thick bead of a second material was then placed on top of the first sealant and the materials were placed in the oven set at 140°F for 168 hr. The materials were determined to be compatible if there was no adhesion failure between the two sealants and if the materials did not revert back to a liquid. The results from the sealant/sealant compatibility testing are also provided in Table 2.

Table 2
Compatibility Test Results

Sealant	Material Tested	Test Results
Dow Corning® 888	Asphalt Concrete	Satisfactory
Dow Corning® 890	Asphalt Concrete	Satisfactory
Koch Product 9050-SL	Asphalt Concrete	Satisfactory
Dow Corning® 888	Dow Corning® 890	Satisfactory
Dow Corning® 888	Koch Product 9050-SL	Satisfactory
Dow Corning® 890	Koch Product 9050-SL	Satisfactory

The results from the compatibility testing indicate that the sealants are compatible with one another and with the asphalt pavement. Therefore, based upon the compatibility testing, any of the alternative sealants could be used to seal the cable slot.

Resilience testing

The resiliency testing was conducted to investigate the ability of the sealant to recover its size and shape after being deformed. In a conventional working joint, the deformation could be caused by slab movement or by debris such as sand and small stones being forced into the sealant. For the sensor cable application, the slots are not working joints, but it is important for the sealant to be able to "push out" or reject small debris thus preventing them from becoming embedded in the sealant.

The resiliency test used for this study is described in Federal Specification SS-S-200E. This specification was developed for two-component, cold-

applied joint sealant materials. The tests consisted of pouring sealant into a small tin which is approximately 70 mm in diameter and 45 mm in depth. The tins were filled flush and the sealant was allowed to cure in the laboratory for 10 days prior to testing. One set of specimens was placed in a forced draft oven set at 158°F for 7 days to investigate the aging characteristics of the sealants. After the sealant had been conditioned in the laboratory for 10 days, the ball penetration tool (see Figure 39) was brought in contact with the sealant surface. The dial gage was zeroed and then the ball tool was forced 1 cm into the sealant, allowed to sit at that position for 5 sec and then released. The amount of rebound or sealant recovery was recorded and reported as percent resilience. Table 3 provides the resilience testing results.

Table 3
Resilience Test Results

	Resilience Results (Percent)	
Sealant Materials[1]	**Unaged**	**Aged**
Dow Corning® 888	90	81
Dow Corning® 890	81	64
Koch Product 9050-SL	45	33
Koch Product 9050-SL[2]	58	65

[1] Samples did not cure full depth.
[2] Data taken from a second batch of sealant material.

None of the samples completely cured to the full depth of the tin. The alternate sealants are moisture curing materials and as the surface cures, the permeability of that surface decreases. This means that it takes longer for the moisture to get to the sealant in the bottom of the tin, increasing the length of time required for complete curing. The Koch Product 9050-SL, however, had only a thin skin of material on the surface which cured. It was expected that this lack of cure was caused by the fact that the shelf-life of the sealant was almost expired. The exact cause of the lack of curing was not determined because the manufacturer removed the sealant from the market.

The specification requirement for unaged and aged resilience in Federal Specification SS-S-200 is a minimum of 75 percent. Both of the Dow Corning materials would have met the unaged requirement and the Dow Corning® 888 material would have also met the aged requirement. The fact that the aged resiliency of the Dow Corning® 890 is less than 75 percent does not infer that it cannot be used in the sensor cable application. The lower recovery value could be attributed to the fact that the sealant was developed to be a softer material than the Dow Corning® 888, or that the sample used to test the aged resiliency cured differently than the unaged sample. The lower modulus of the Dow Corning® 890 and ease of installation should outweigh

any potential problems that would be associated with an aged resilience of the less than 75 percent.

Fuel Resistance

Joint sealant materials that are used in areas where fuel and lubricant spillage could occur are often tested to determine their resistance to those materials. Often it is not practical to test the sealant material using each of the fuels or lubricants to which it could be exposed. Therefore, a standard method has been established in Federal Specification SS-S-200E, Federal Specification SS-S-1614A, American Society for Testing and Materials (ASTM) D 3569, and ASTM D 3581, for evaluating the resistance of sealants to fuels and lubricants. The solvent used in the fuel resistance test is Reference Fuel B (a mixture of 70 percent isooctane by volume and 30 percent toluene).

The test specimens were prepared by pouring sealant material into a tin which measured 55 mm in diameter and 35 mm in depth. The sealant was allowed to cure for 10 days and then the specimens were immersed for 24 hr in the Reference fuel at a temperature of 120°F. After the 24 hr immersion, the specimens were either blotted off and weighed, placed in front of a fan for 1 hr and weighed, or placed in an oven set at 158°F for 4 hr and then weighed. The different drying methods were used to provide an indication of the initial change in weight if a fuel was spilled on the sealant and then how the sealant would change as the fuel evaporated. Table 4 provides the fuel resistance test results.

The specification requirements for the fan dried testing is a 2 percent maximum (Federal Specification SS-S-200E) and the requirement for the oven dried specimens is a five percent maximum (Federal Specification SS-S-200D). Both of the silicone materials conform to the Federal Specification SS-S-200D requirement. The silicone materials do not conform to the Federal Specification SS-S-200E requirement, but there has not been any reported complaints from the field concerning the lack of fuel resistance of the Dow Corning® 888 material when used in the sensor cable application. Therefore, it is expected that the fact that, as the fuel evaporates, the sealant returns to its original weight and size infers that fuel resistance of the silicone sealants for this application is satisfactory.

Table 4
Fuel Resistance Test Results

Sealant Material[1]	Change In Weight (Percent)		
	No Drying	Fan Dried	Oven Dried
Dow Corning® 888	21.3	8.6	3.5
Dow Corning® 890	39.0	12.4	4.6
Koch Product 9050-SL[2]	***	0.2	***

[1] Samples did not cure full depth.
[2] Samples did not cure enough to test. The test result provided was taken from a different batch number.

Surface Slope

One potential advantage of using sealants such as the Dow Corning® 890-SL material is the fact that they are self-leveling and therefore labor costs associated with "tooling" or smoothing out a non-sag material are eliminated. With this advantage comes a potential disadvantage of the sealant material flowing out of the joint if the slope of the pavement is too great. The question then becomes how much of a slope is allowable before a non-sag material must be used.

To investigate this problem, the test procedure listed in Federal Specification SS-S-200 was modified to detect flow versus slope. In this test, a channel with a joint reservoir measuring 0.5 in. wide by 1.0 in. deep by 12 in. long is over filled with sealant material. The sealant material is struck off level with the surface of the channel and the channel is placed on a 1.5 percent slope. The difference between the surface of the sealant and the top of the raised portion of the channel is determined after a 24 hr curing period. A deviation of greater than 0.063 in. is classified as a failure. In addition to the 1.5 percent incline, the Dow Corning® 890-SL material was also placed in channels having slopes of approximately 4, 8, 13 percent. The test was conducted at room temperature (approximately 73°F) and at 0°F. Table 5 provides the results of the inclined tests. Originally, Koch Materials Product 9050-SL was to be tested in addition to the 890-SL, but this material has been removed from the market (Koch Materials will no longer produce polysulfide or coal tar sealants).

Table 5
Results of the Raised Incline Testing

Percent Slope	Results at 73°F	Results at 0°F
1.5	0.04 in.	0.04 in.
4	0.25 in.	0.08 in.
8	0.4 in.	0.2 in.
13	0.5 in.	0.4 in.

These results indicate that if a joint sealant depth of 1/4 in. is used that all of the material could potentially be lost if the slope is 4 percent. Generally, the slopes used in pavement construction are 2 percent or less, therefore it is expected that for a sealant depth of less than 1/4 in., approximately 1/2 or less of the material will be lost at the very top portion of the slope. This would leave a sealant depth of approximately 1/8 in. For the sensor cable application, 1/8 in. of sealant in small areas at the top of a slope would probably be acceptable. To overcome the problem, a 1/2 in. sealant depth could be used at the tops of the slope or the joint could be "touched up" the next day.

Fourier Transform Infrared Spectroscopy Analysis

Fourier Transform Infrared spectroscopy using the attenuated total reflectance (FTIR-ATR) technique is a chemical analysis methodology that has been used by the polymer industry as a quality control tool and forensic analysis method. In addition, FTIR-ATR has been used on a limited basis as a forensic analysis tool for pavement joint sealants (Graham and Lynch 1992, and Lewandowski et. al. 1992) and as a quantitative method for determining the percentage of a modifier that has been added to an asphalt cement binder (Anderton and Lewandowski 1992).

FTIR is based upon the principle that most organic compounds absorb energy in the infrared region. When an infrared beam of radiation is passed through a sample, the covalent bonds of the different functional groups absorb energy at specific characteristic frequencies. A plot of the amount of energy absorbed by a sample versus frequency is called a spectrum. An example of a spectrum is shown in Figure 40. The peaks evident in the spectrum indicate specific chemical functional groups. The reason FTIR analysis is of interest in this investigation is that it could potentially be used as a quality control tool during sealant installation.

The ATR technique allows the spectra of solid materials to be obtained. This is accomplished by placing the joint sealant material (laboratory prepared or field obtained) on an internal reflectance element (IRE). In this

investigation, a germanium (Ge) crystal was used for the IRE. The Ge crystal was selected to prevent the potential of having regions that were totally absorbing (i.e., exceeding the maximum detector response).

The sample and IRE were then placed into the FTIR sample compartment where an infrared beam of energy was passed through the IRE. The IRE causes the beam to undergo multiple internal reflections which creates an effect called the evanescent wave. The beam is then collected by the detector and is converted to the type of spectra shown in Figure 40.

FTIR procedure and results

A Nicolet 510P FTIR spectrometer with a Michelson Interferometer and a Deuterium Triglyceride detector was used to collect the spectra. The experimental procedure consisted of first collecting a background signal through the IRE and then placing the joint sealant sample on the IRE and collecting the signal through the sample. The spectra was obtained by ratioing the background signal to the sample signal. The FTIR sample area was continually purged with nitrogen to remove carbon dioxide and water vapor from the system. The collection parameters used to obtain the spectra were 32 scans at a resolution of 4 cm^{-1}.

The spectra presented in these figures can provide information on the constituents used to produce the sealants and potentially aid in the detection of contaminates that could lead to failure in the field. Without information concerning the sealant formulation, it is difficult to positively identify all of the chemical constituents in the material. However, using the information provided in the Material Safety Data Sheets (MSDS's), one can verify the presence of a constituent. One problem using MSDS's in this manner is that they only list hazardous or regulated constituents. Therefore, to obtain a complete chemical make-up of the sealant, a technique such as Nuclear Magnetic Resonance (NMR) or mass spectroscopy should be coupled with FTIR. Table 6 provides the wavenumber assignments of various chemical functional groups or where peaks would be expected if the functional group is present.

Representative FTIR-ATR spectra for each of the sealants analyzed in this study are presented in Figures 41-44. The spectra are those of actual samples collected from the field.

Thermogravimetric Analysis

Thermogravimetric analysis (TGA) measures weight loss, both amount and rate), of a material as a function of temperature or time in a controlled atmosphere. The test consists of placing a small sample (usually less than

25 mg) onto a balance which is placed into a furnace. A temperature rate or the length of time at an isothermal temperature is then programmed into the computer controls and the change in weight of the sample is recorded.

TGA assists in the determination of the thermal and/or oxidative stability of a material as well as providing information on material consistency and product performance. In this investigation, TGA was used to provide an indication of thermal stability and when combined with FTIR-ATR spectra to provide a better fingerprint of the sealant. Often it is difficult to use just one test method to positively identify a sealant material or a contaminate in a sealant. By developing a baseline using FTIR-ATR and TGA it may be possible to develop quality control tools that will inform the user agency of the quality of the sealant within 2 or 3 days instead of 3 to 6 weeks.

Figure 45 provides thermograms of the sealant materials after they had cured in the laboratory for 28 days. The thermograms indicate that the Dow Corning sealants are thermally stable up to a temperature of approximately 380°C. The high thermal stability infers that the sealant could withstand aircraft exhaust for limited periods of time without significant damage. This type of stability would be more important for joints in pavements that would receive excessive aircraft exhaust like runway ends and hardstands. For the sensor cable application, it is simply an added benefit.

If the thermograms were to be used for quality control purposes, the curve profile becomes important. The curve is relatively flat until the initial weight loss, then the weight loss occurs rapidly. If the sealant was contaminated, the amount or rate of weight loss would be affected.

Dynamic Shear Rheology

Dynamic Shear Rheology (DSR) is an analytical methodology used to characterize the viscoelastic behavior of materials. Viscoelasticity infers that the material being characterized has an elastic response and a viscous response and the effect of each response is dependent upon the test conditions (i.e., the strain rate or frequency and temperature).

DSR was developed to investigate polymeric systems but has been adopted by other disciplines as a means to characterize the properties of materials for performance based specifications. One example of the growing acceptance of DSR is its inclusion in the Strategic Highway Research Program (SHRP) asphalt binder specification which is a performance based specification (Anderson and Christensen 1992)

The greatest potential of the DSR is its ability to characterize the properties of a material over a wide range of temperatures and frequencies or rates of loading. This characterization is achieved through a technique known as time-temperature superposition. Time-temperature is based on the premise that a

material will respond or behave at low temperatures in the same manner it responds to high rates of loading and the material will respond at high temperatures in the same manner it responds at long loading times. Therefore, a series of tests can be conducted over a specified frequency range at a constant temperature to determine the material response at those test conditions. Additional tests are conducted over the same specified frequency range at various isothermal temperatures. The curves developed from these isothermal tests are then shifted horizontally to develop a mastercurve of the material property versus frequency or temperature. The equation most often used to shift the isothermal curves is the Williams-Landel-Ferry (WLF) equation. The WLF equation is as follows:

$$\log a_T = -C1(T - T_R)/C2 + (T - T_r)$$

where:

a_T	=	horizontal shift factor
C1, C2	=	material constants related to the reference temperature
T_R	=	reference temperature of the isothermal curve to which the other data is being shifted
T	=	isothermal temperature of the data being shifted

A small vertical shift may also be required. The vertical shift, denoted as b_T, corrects for changes in material density that may occur as the temperature is changed from one isothermal test temperature to the next.

Figure 46 provides a mastercurve of a typical amorphous, glass forming, uncrosslinked elastomer. The mastercurve can be divided into four distinct regions. At short testing times (high frequency/low temperature), the polymer responds as a glassy, brittle material and the glassy modulus (G_g) is several orders of magnitude higher than at any other point on the mastercurve. This region is referred to as the glassy plateau. As the testing time increases (frequency decreases/temperature increases), the material exhibits a transition from the glassy state to a rubber state. This transition is often termed the leathery transition. The glass transition temperature (T_g) of the material is located in this region. The third region or rubbery plateau occurs as the frequency continues to decrease (temperature increases). The rubbery plateau region is generally the desired working range for a joint sealant material. The fourth region on the mastercurve is where the material begins to flow.

Experimental

There are several sample configurations that can be employed using DSR. Some typical configurations are cone and plate, rectangular torsion, and parallel plates. Parallel plates were selected to conduct this initial study because of the ease of sample preparation. The samples are simply punched out to the desired diameter and inserted between the two plates to conduct the test.

The procedures used to test the materials consisted of punching out a sample, placing the sample in the Bohlin VOR Rheometer (controlled strain), setting the plate gap, and conducting a strain sweep or oscillation test. The strain sweep allows the linear viscoelastic region of the sample to be determined by incrementally increasing the strain at a constant temperature and frequency.

DSR imparts a dynamic load onto a material using a sinusoidal shear strain. The response to this loading is measured resulting in G', G", and tan δ where G' is the storage modulus or the elastic response of the material and G" is the loss modulus or the viscous response of the material. Tan δ is a measurement of the damping ability of the material where δ is the phase angle between the induced load and measured response. Tan δ is also equal to the ratio G"/G' and the maximum tan δ is associated with the glass transition of the material.

What makes DSR particularly interesting as far as this study was concerned was the fact that a mastercurve relating to the physical properties of a sealant could be generated in 1 day after the material had cured. The tests used to determine if the sealants were acceptable alternates took from 1 to 2 weeks after the material had cured. The DSR data also indicates the temperature susceptibility of the sealant materials. Figure 47 provides the mastercurves for the sealant materials evaluated.

The mastercurves that were developed for the sealants only include the rubbery plateau. Notice that the silicone materials have a relatively flat slope indicating that the complex modulus (G*) or stiffness of the sealant is less sensitive to temperature and rate of loading. The Koch Product 9050-SL material; however, has a large slope indicating that as the temperature decreases or rate of loading increases, the material becomes more brittle.

Evaluation of Will-Seal™ 150

The evaluation of Will-Seal™ 150 is discussed separately because it is a preformed material. Therefore, the tests used to evaluate the suitability of Will-Seal™ 150 for sensor cable application are different from those used for the other alternative sealants. The testing was conducted to determine the material properties of the Will-Seal™ 150 including fuel resistance, water

absorption potential, heat/melting resistance, blast resistance, bonding potential, and buckling resistance.

Will-Seal™ 150 is supplied in various sizes and the depth of the material is fixed for a given width. For example, if the joint width is 3/4 in., the recommended material size would be 1.5 in. wide. The depth of this material would be 1.5 in. Combining the seal depth with the 1/4 in. recess below the pavement surface and the thickness of the cable would yield a depth greater than 2 in. (currently the standard used for sensor cable installation). Smaller width tapes would have smaller depths and it may be possible to use a 1 in. wide tape which would have a 1 in. depth. This would make the cable/seal/ recess depth approximately 1.9 in. The final width that would be required for a particular joint configuration would have to be determined through field tests. It is expected that the physical dimensions of the seal could be adjusted to accommodate sensor cable installation.

The bonding potential, fuel resistance, and water absorption potential of the material was combined into one series of tests. These tests were conducted by preparing bond specimens, conditioning the samples, and then using an Instron to determine tensile properties. Specifically, 15 bond specimens were prepared by cutting 2 in. long strips of seal from a roll of material. The material was placed between two concrete blocks which formed a joint reservoir that measured 1/2 in. wide by 2 in. deep by 2 in. in length. All of the specimens were conditioned in the laboratory for 24 hr before additional conditioning and/or testing. The specimens were also held in compression throughout the conditioning. After the 24-hr conditioning in the laboratory, three of the samples were tested for flame resistance in accordance with Federal Specification SS-S-200E and three of the specimens were tested in tension on an Instron Machine at a strain rate of 1/2 in./min. Six samples were placed in Reference Fuel B as specified in Federal Specification SS-S-200 for fuel immersed bond testing. After the 24 hr immersion, three of the samples were allowed to dry for 1 hr at standard laboratory conditions and three were placed in a forced-draft oven for four hr. The temperature of the oven was set at 158°F (70°C). The specimens were then tested using the Instron machine.

The remaining three samples were immersed in water for 96 hr as specified in Federal Specification SS-S-1614A. After the water immersion, the samples were dried off and tested using the Instron machine.

Table 7 provides a summary of the Instron testing of the Will-Seal™ 150 material. The data indicate the bonding potential as indicated through tensile testing decreases with exposure to fuel but is not necessarily decreased upon exposure to immersion in water. However, the variability of the bonding potential results do increase as the seal is exposed to various types of conditioning. The initial gage length of the specimens tested using the Instron was 0.5 in. The displacement at the maximum load for all of the conditioned specimens ranged from 0.04 to 0.08 in. These results indicate that the maximum bonding potential could be exceeded at very low joint movements.

This however should not be a problem for two reasons. The joints into which the material would be placed are non-working joints and therefore no movement should occur. In addition, the strain rate at which these tests were conducted is much larger than the seal would experience in the field. The slower strain rate in the field would allow the Will-Seal™ 150 to expand to the new width placing the material back into compression.

Table 7
Summarized Instron Testing of Will-Seal™ 150

Sample Conditioning	Maximum Load, lb	Displacement at Maximum Load, in.
Nonimmersed	25.3 (S.D. = 1.7)	0.07 (S.D. = 0.04)
Fuel-Immersed	13.5 (S.D. = 2.4)	0.06 (S.D. = 0.01)
Fuel-Immersed with Oven Drying	10.8 (S.D. = 4.5)	0.04 (S.D. = 0.01)
Water-Immersed	29.5 (S.D. = 3.2)	0.08 (S.D. = 0.01)

The Will-Seal™ 150 material was also tested for water absorption by cutting three 2-in. strips from the roll. The strips of material were weighed in air and then submerged in water for 24 hr. These specimens were not held in compression. After 24 hr, the samples were surfaced dried and weighed. Each of the three samples expanded from the original 0.5 width to approximately 4.5 to 5 in. and each sample absorbed approximately 61 percent water. The actual amount of water that the Will-Seal™ 150 would absorb in the field would be dependent upon the amount of expansion in width that occurred. If the material that was tested in the laboratory was placed in a 0.5 in. wide joint, it is expected that the amount of water absorption would be less than 2 percent. This amount of absorption should not adversely affect the field performance of the seal.

The heat/melting resistance was investigated using two techniques. The first technique was the flame resistance test that is specified in Federal Specification SS-S-200E. This test consists of preparing three bond specimens (as described above) and exposing one surface of the seal to 500°F (260°C) for 120 sec. The seal is then examined for blistering, charring, melting, or any other defect. The Will-Seal™ 150 did not exhibit any defects after exposure to the Federal Specification SS-S-200 flame test.

The second technique used was a differential scanning calorimetry (DSC). Temperature induced material transitions such as the glass transition temperature (T_g), the melting temperature (T_m), and the decomposition temperature can potentially be detected if they exist. The DSC indicated that the Will-Seal™ 150 has a T_g of approximately -19.9°F (-28.8°C). This implies that at temperatures below -20°F, the seal material will be very brittle and

could shatter if joint movement occurred. By contrast, the T_g of silicone type materials is approximately -180°F. Since the seal will be placed in a non-working joint, joint movement should not be a major concern. The decomposition temperature of the Will-Seal™ 150 is approximately 374 to 500°F (190 to 260°C). The discrepancy between the decomposition temperature determined by the DSC and apparent satisfactory performance when tested in accordance with the flame resistance of Federal Specification SS-S-200 is probably due to the difference in sample size. The approximate sample size used in the DSC was 8 to 20 milligrams. The sample size used in the flame test was approximately 50 to 55 grams.

The material property analysis of the Will-Seal™ 150 material indicates that the material could probably be used satisfactorily in sensor cable installation. However, if this material is used it may be necessary to increase the depth of the joint cut into the pavement to ensure there is enough room for the manufacturer's recommended seal size, the 1/4 in. recess, and the cable. Also the material cost is significantly higher than the silicone type materials currently used.

Installation of the Will-Seal™ 150 would not require any special equipment because it would be hand installed. However, if the material is not inserted immediately into the joint, it could expand to such an extent that insertion into the joint would be almost impossible. The 1/4 in. recess of the seal is critical when using the Will-Seal™ 150. The bond specimens prepared in the laboratory all exhibited a swelling of the material above the concrete blocks. The swelling was approximately 1/4 in. above the surface. The effects of this swelling on cut slots in ACC should be investigated during the field evaluation in a northern tier site.

Slot Configuration Testing

There were two main concerns associated with changing the sealant/slot configuration. The first concern was that the cable would buckle as the ambient temperature increased and push the sealant out of the slot. The second concern was that by eliminating the encapsulation of the cable in the sealant, water would infiltrate the slot and decrease the effectiveness of the sensor cable.

PCC is a permeable substrate; therefore, some moisture may infiltrate the cable slot but the slot should not become saturated or be free flowing. It is expected that the amount of moisture in the slot will be less than the amount of moisture the cable would be exposed in a sand bed under an ACC pavement or when the cable is installed in an unpaved area. Based upon these observations, the moisture in the slot should not adversely affect the cable sensor effectiveness.

A buckling test was used to evaluate the sealant's ability to hold the cable within the pavement slot during an increase in temperature. Two sealant-cable installation configurations were used in the buckling test. The standard configuration (shown in Figure 48) has been used successfully for many years, but requires a significant amount of sealant to encapsulate the cable. Figure 49 shows the new proposed configuration which uses a backer rod to replace a portion of the sealant and omits encapsulating the cable. Sealants used to anchor the cable within the beam slots included Dow Corning 888, Dow Corning 890, and Koch 9050. The test was conducted by preparing PCC beams that were 6 in. wide by 6 in. deep by 24 in. long, sawing a slot along the length of the beam, and inserting the cable, backer rod, and sealant into the slot. The sealant was allowed to cure for a minimum of 10 days and then an axial load applied to the cable ends to produce a buckling condition.

A PCCS sensor cable was used for the buckling portion of the laboratory study. The PCCS cable was a 0.577 in. diameter copper wrapped coaxial cable with a 0.188 in. diameter copper core. Test results of the buckling test are given in Table 8 and shown in Figures 50-54. Values given in Table 9 represent the loads that can be induced in the PCCS cable by increases in temperature when the cable ends are fixed and prevented from expanding. These thermal load values were calculated using the modulus of elasticity value for copper, the calculated cross-sectional area of the copper core, and the effective coefficient of thermal expansion. The effective coefficient of thermal expansion represents the difference between the coefficients for copper, (9.3×10^{-6} in./in./°F) (American Institute of Steel Construction 1965) and PCC (6.0×10^{-6} in./in./°F) (Higdon et al. 1960). The effective coefficient was used because the PCC pavement will expand as the cable expands, but the pavement expansion will be less than the cable. A temperature increase of 50 to 60 °F could probably be the maximum change expected from the temperature at the time of cable installation and the high temperature expected 1 to 2 in. below the pavement surface. Using an increase of 60 °F, a maximum thermal loading of 82 lbs. is possible.

Comparison of the bucking test results shown in Figures 53 and 54 indicated that the loads needed to fail the standard configuration of cable-sealant (CS) were consistently higher than the new proposed sealant-cable-backer rod (SCB) configuration. However, the loads needed to fail the SCB configuration were higher than expected thermal loads. Consequently, the new SCB configuration should anchor the PCCS cable in the sealed slot.

Conclusions

The results of testing and evaluation of the sealants and the slot configuration lead to the following conclusions.

a. The compatibility of the Dow Corning® 888, Dow Corning® 890, and the Koch 9050-SL to asphalt concrete and also between sealants proved to be satisfactory.

b. Only the Dow Corning® 888 met both the unaged and aged resilience requirements. Neither the Dow Corning® 888 or 890 cured completely before testing. However, the Dow Corning® 890 is expected to reject incompressibles and rebound from deformation. The Koch 9050 sealant submitted for testing did not cure enough to test. An expired shelf-life of the Koch 9050 sealant was believed to be the reason for lack of curing and Koch has since removed the 9050-SL sealant from the market.

c. When exposed to fuel, both the Dow Corning® 888 and Dow Corning® 890 sealants absorbed fuel, as noted by a weight gain. However, after oven drying to evaporate the fuel, the sealant returned to within 5 percent of the original weight, which indicates that the fuel resistance for slot application is satisfactory.

d. The self-leveling sealant Dow Corning® 890 was tested to determine its potential to flow from the slot of a sloped surface. At the standard test slope of 1.5 percent, the Dow Corning® 890 sealant had satisfactory results. However, if the slope increases, the flow of the sealant from the slot can be expected to increase to an extent that some "touch up" may be needed the next day.

e. FTIR and TGA testing can provide information on the constituents used to produce the sealants and potentially aid in the detection of contaminates that could lead to failure in the field.

f. DSR evaluates physical properties of a sealant and can indicate the temperature susceptibility of the sealant. Mastercurves for all the silicone sealants were relatively flat indicating the sealants' stiffness were less sensitive to temperature and rate of loading than the Koch 9050-SL sealant. The Koch 9050-SL had a large slope on the mastercurve, which indicated the material can become more brittle as the temperature decreases.

g. Material property analysis of the Will-Seal™ 150 indicates that the seal could probably be used satisfactorily in sensor cable installation provided the slot or joint is non-working or no movement occurs. However, it may be necessary to increase the depth of the slot cut to ensure there is enough room for the seal, the 1/4 in. recess, and the sensor cable.

h. Bucking tests of to slot and sealant configuration indicated that the loads needed to fail the standard configuration of cable-sealant (CS) were consistently higher than the new proposed sealant-cable-backer rod (SCB) configuration. However, the loads needed to fail the SCB configuration were higher than expected thermal loads. Consequently, the new SCB configuration should anchor the PCCS cable in the sealed slot.

Recommendations

Recommendations related to installation of Dow Corning® 890, Koch 9050-SL, and Will-Seal™ 150 sealant materials and the proposed modified slot and cable configuration are summarized as follows.

a. Dow Corning® 890 self leveling sealant may be substituted for the Dow Corning® 888. Some "touch up" of the sealant on sloped surfaces may be required.

b. Based on the DSR mastercurves, other silicone sealants, such as Miles Baysilone 960 and Crafco RoadSaver Silicone, can be used as substitutes for Dow Corning® 888 sealant.

c. Will-Seal™ 150 can be substituted for the Dow Corning® 888 provided no movement of the portland cement concrete joint or slot is anticipated. Will-Seal™ 150 can become brittle below -20°F. In addition, slot geometry must be considered to account for the depth of the compressed seal, seal recess, and cable.

d. In order to reduce cost, the current slot and sealant configuration can be modified by including a backer rod as a replacement for some of the silicone sealant. The backer rod must be sized for the slot width to prevent replacing to much sealant. The thickness of the sealant above the backer rod should never be less than 1/4 in.

e. The modified sealant-cable-backer rod configuration and the Dow Corning® 890 and Will-Seal™ 150 should be field tested and evaluated before full implementation.

Table 8
Thermal Loading Estimate for PCCS Cable

Temperature Change, Δt °F	Cross Sectional Area, A in.^{2}	Modulus of Elasticity, E* psi	Expansion Coefficient, ε in./in./°F	Thermal Load, P** lb
10	0.02761	15×10^6	3.3×10^{-6}	14
20				27
30				41
40				55
50				68
60				82
70				96
80				109

* Modulus of Elasticity for Copper (Mantell 1958).
** $P = AE\varepsilon\Delta t$ (Godwin 1984).

Table 9
Results of Buckling Test on PCCS Cable

Specimen No.	Sealant Type *	Configuration **	Maximum Load lb
1	9050	CS	647
2	9050	SCB	390
3	890	CS	738
4	890	CS	708
5	890	SCB	731
6	890	SCB	154
7	888	CS	840
8	888	CS	693
9	888	SCB	647
10	888	SCB	412

* 888 and 890 are Dow Corning sealants.
9050 is Koch sealant.
** CS is the Cable-Sealant configuration.
SCB is the Sealant-Cable-Backer rod configuration.

References

American Institute of Steel Construction. (1965). *Manual of steel construction*, 6th ed., American Institute of Steel Construction, New York, NY, 6-11.

Anderson, D. A. and Christensen, D. W. (1992). "Interpretation of dynamic mechanical test data for paving grade asphalt cements," *Proceedings of the Association of Asphalt Paving Technologists*, Vol 61, Feb. 1992, pp. 67-116, St. Paul, MN.

Anderton, G. and Lewandowski, L. (1992). "Additives in bituminous materials and fuel resistant sealers," Draft report for Federal Aviation Administration, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Godwin, Lenford N. (1984). "Short perimeter intrusion radar and ported coaxial cable sensor slot/seal study," Miscellaneous Paper EL-84-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Higdon, A., Ohlsen, Edward H., and Stiles, William B. (1960). *Mechanics of materials*, Wiley, New York, NY, 473.

Lewandowski, L. H., Lynch, L., Dorman C., and McKnight H. (1992). "The application of dynamic mechanical analysis to the characterization of field-molded joint sealants," Pavement Systems Division 1992 Workshop - Crack and Joint Sealing for Rigid and Flexible Pavements Proceedings, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lynch, G., Graham, R., and Lynch L. (1992). "The emerging investigative field of pavement joint sealants," Pavement Systems Division 1992 Workshop - Crack and Joint Sealing for Rigid and Flexible Pavements Proceedings, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lynch, L. and Graham, R. (1992). "Forensic analysis techniques for joint sealant," *Materials Performance and Prevention of Deficiencies and Failures, Proceedings of the Materials Engineering Congress,* American Society of Civil Engineers, 1992, pp 404-414, New York, NY.

Mantell, Charles L. (1958). *Engineering material handbook*, McGraw-Hill. New York, NY, 7-17.

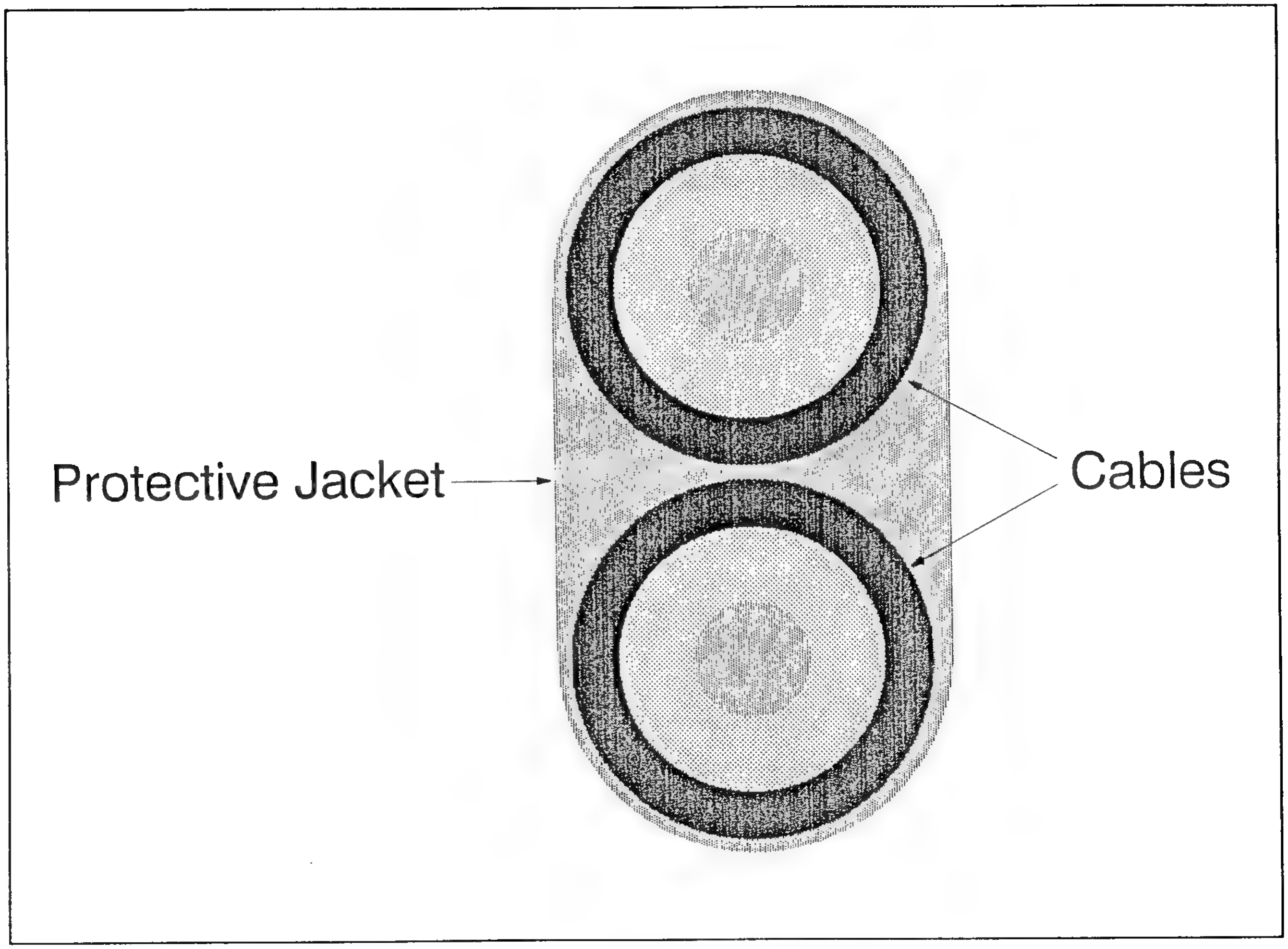


Figure 1. General construction of the TR1 sensor cable

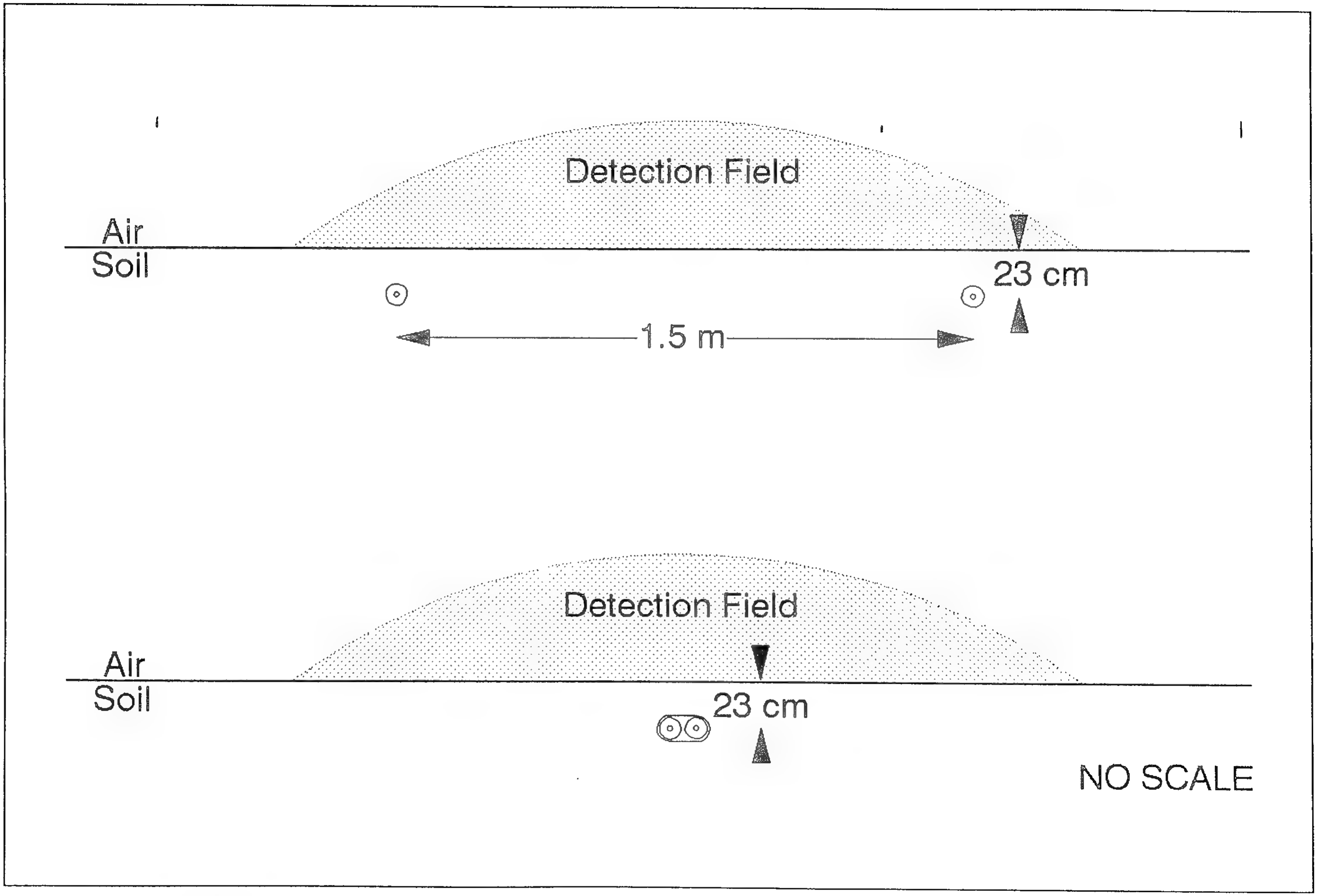


Figure 2. Typical deployment configurations for traditional two-cable sensors (top) and the TR1 sensor cable (bottom)

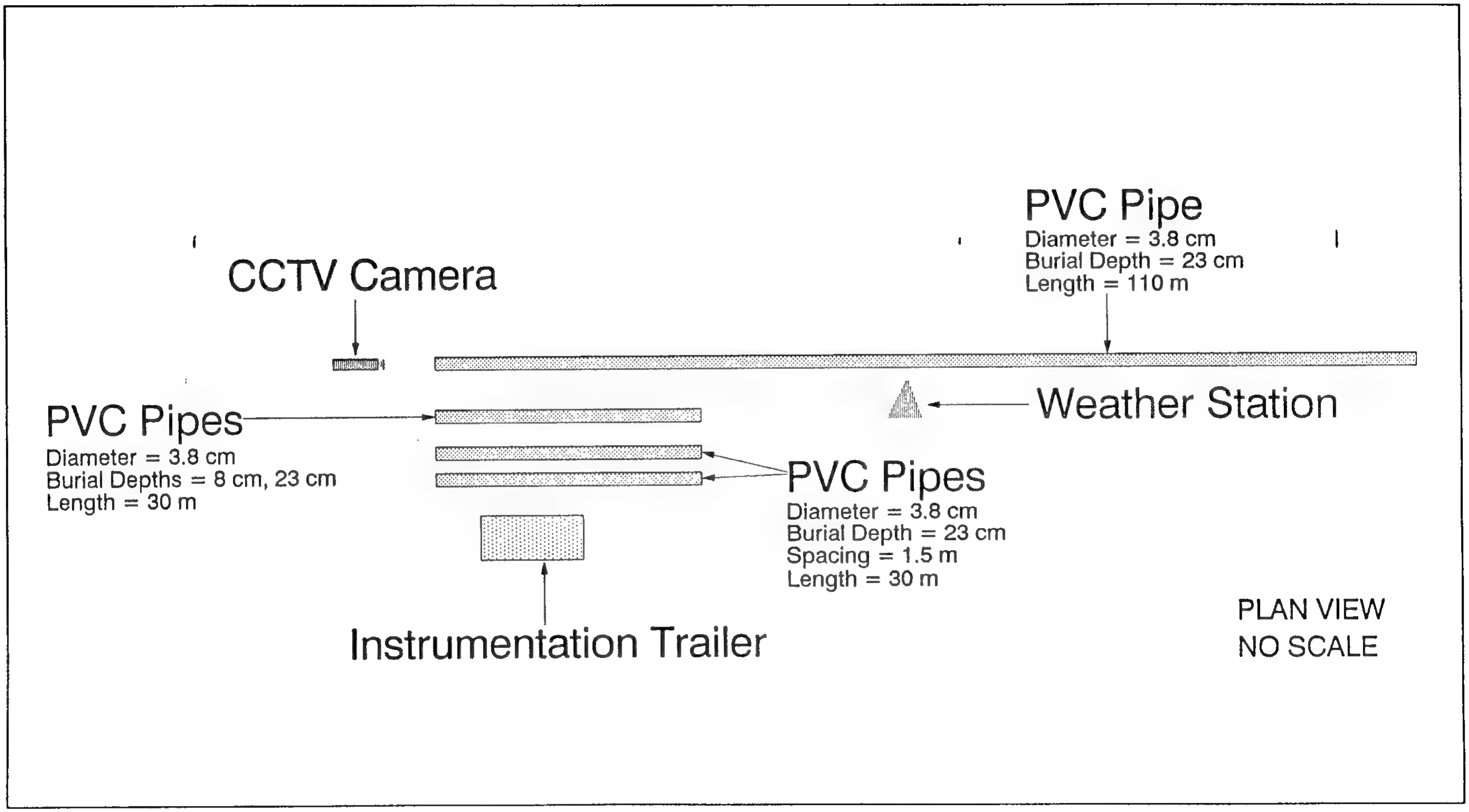


Figure 3. WES site layout

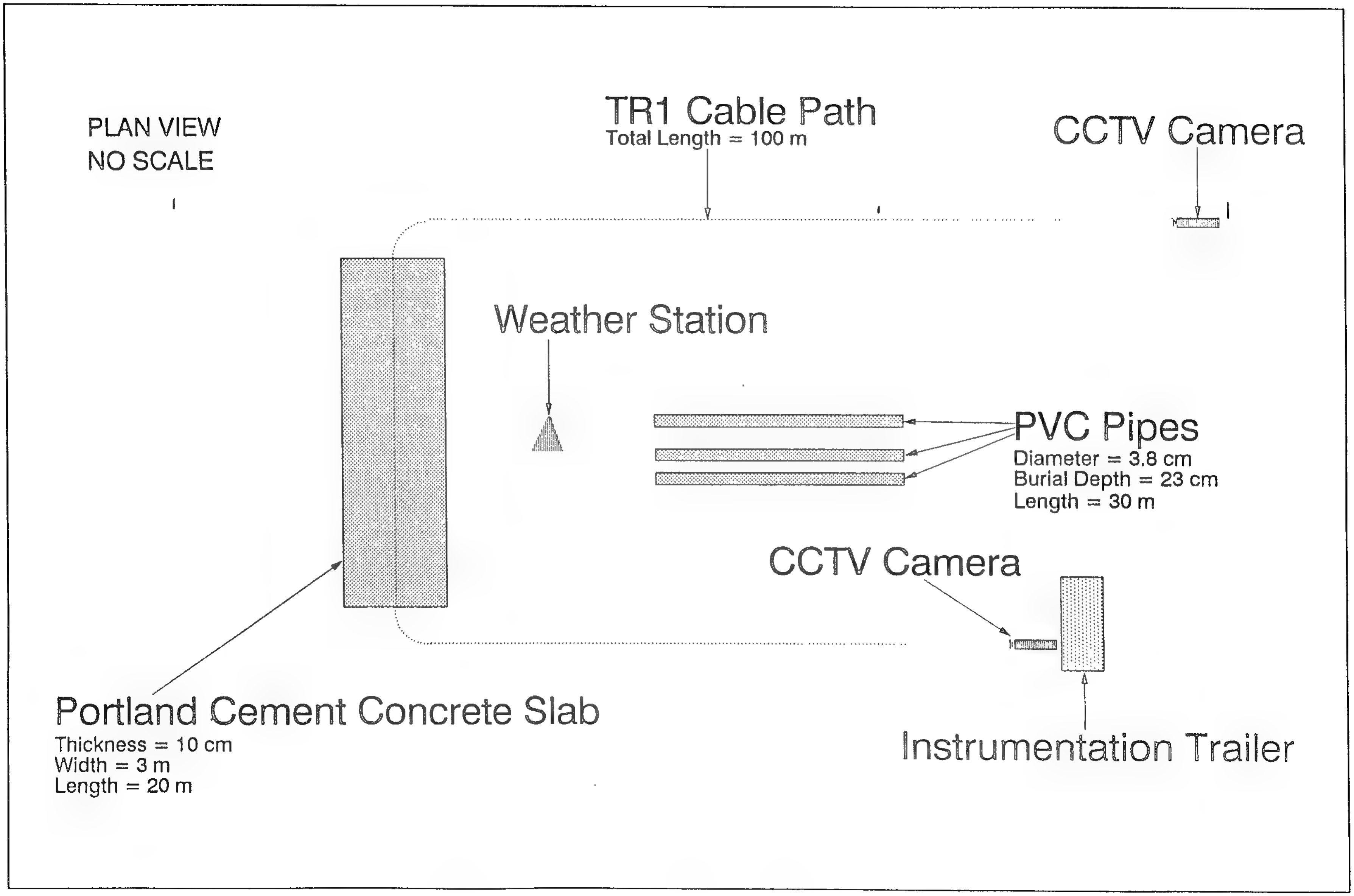
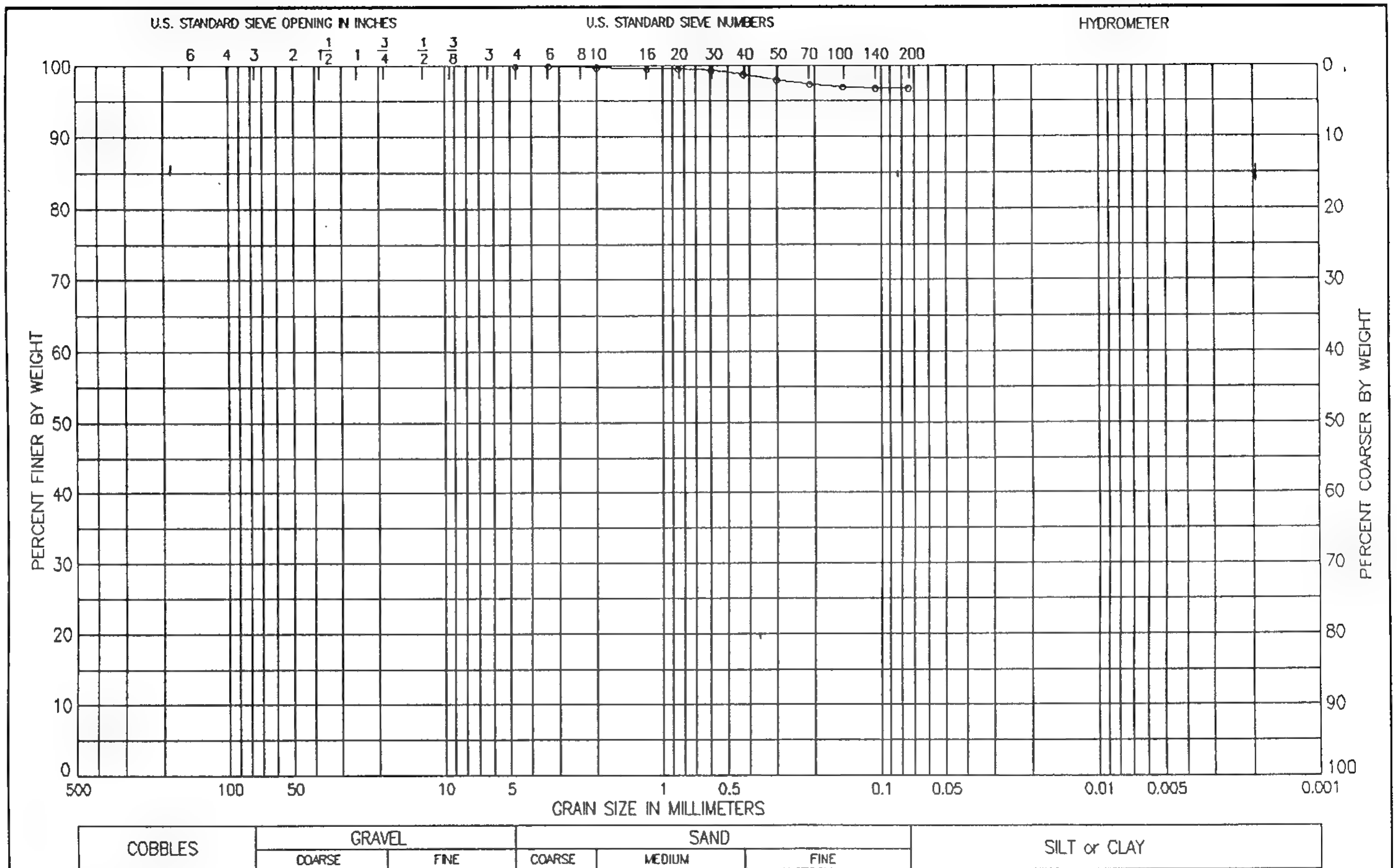


Figure 4. BBTS layout



LL 39	PL 25	PI 14	GS	NAT W,%	ORG,%

CLASSIFICATION
SILTY CLAY (CL), BROWN; TRACE OF SAND

PROJECT BURIED CABLE TESTS

BORING NO. WES SOIL SAMPLE NO.

DEPTH/ELEV DATE 28 JUL 94

GRADATION CURVE — LABORATORY USAE WES – STF/GL

Figure 5. Results of physical properties testing of WES soil sample

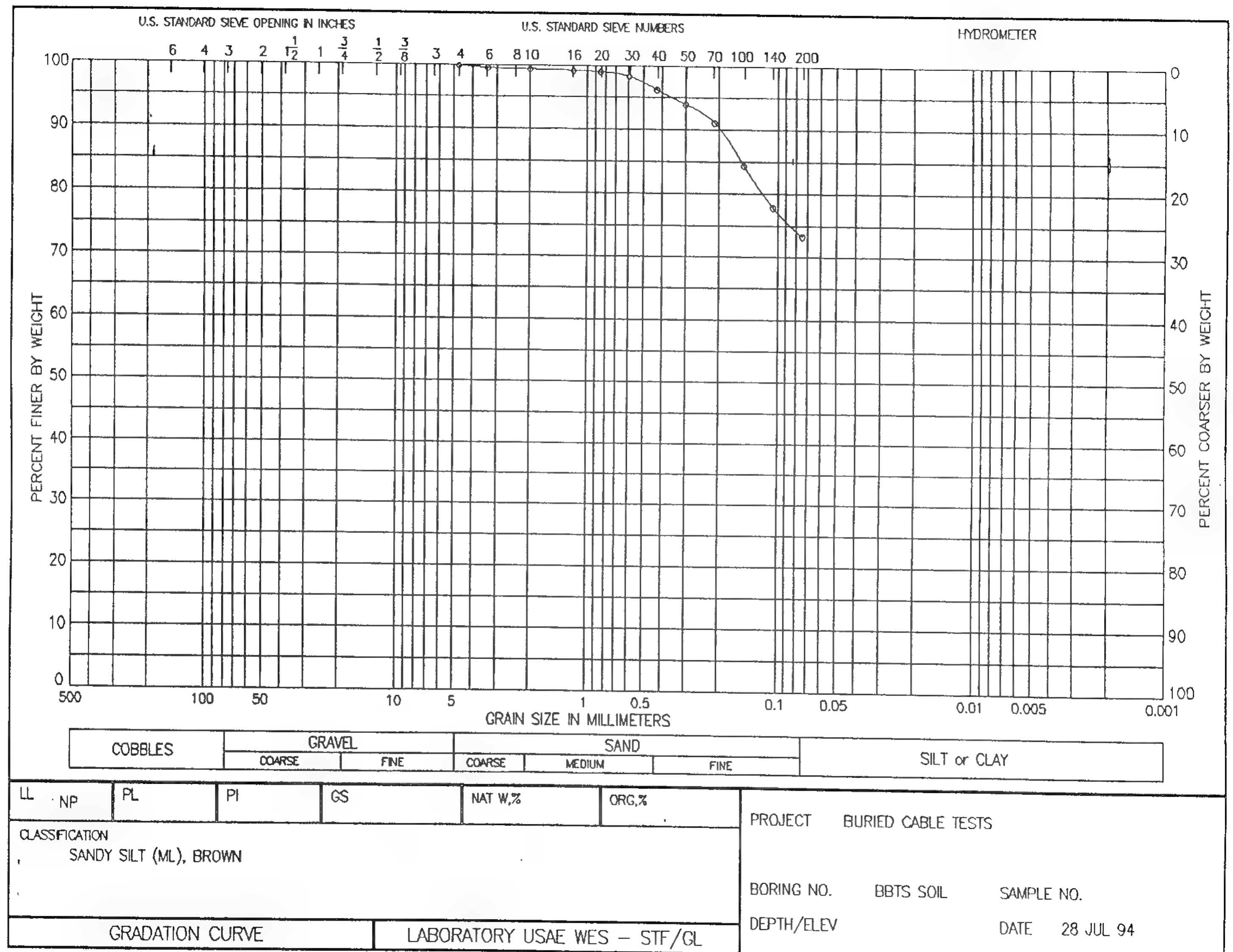


Figure 6. Results of physical properties testing of BBTS soil sample

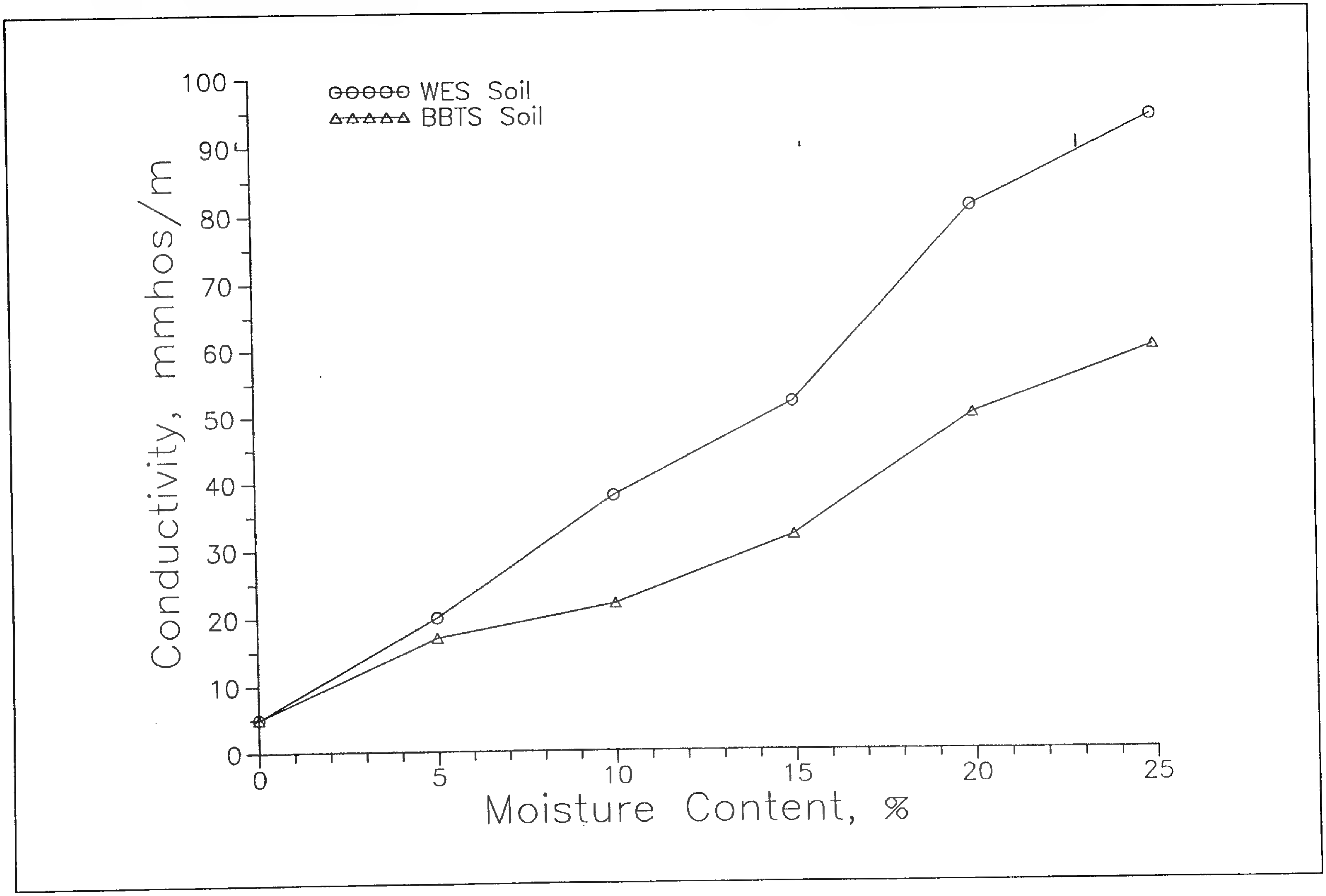


Figure 7. Results of laboratory conductivity testing of WES and BBTS soil samples

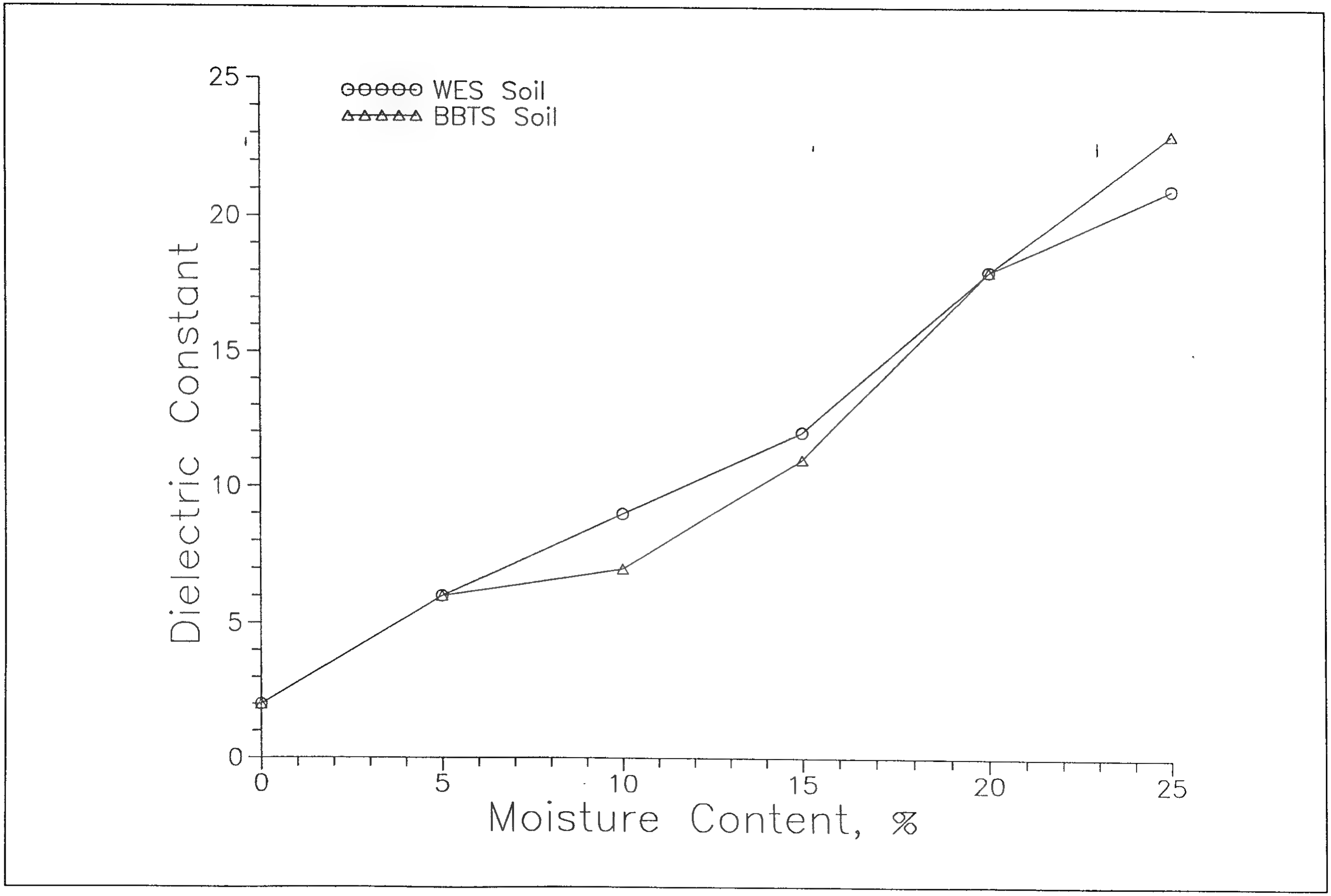


Figure 8. Results of laboratory dielectric constant testing of WES and BBTS soil samples

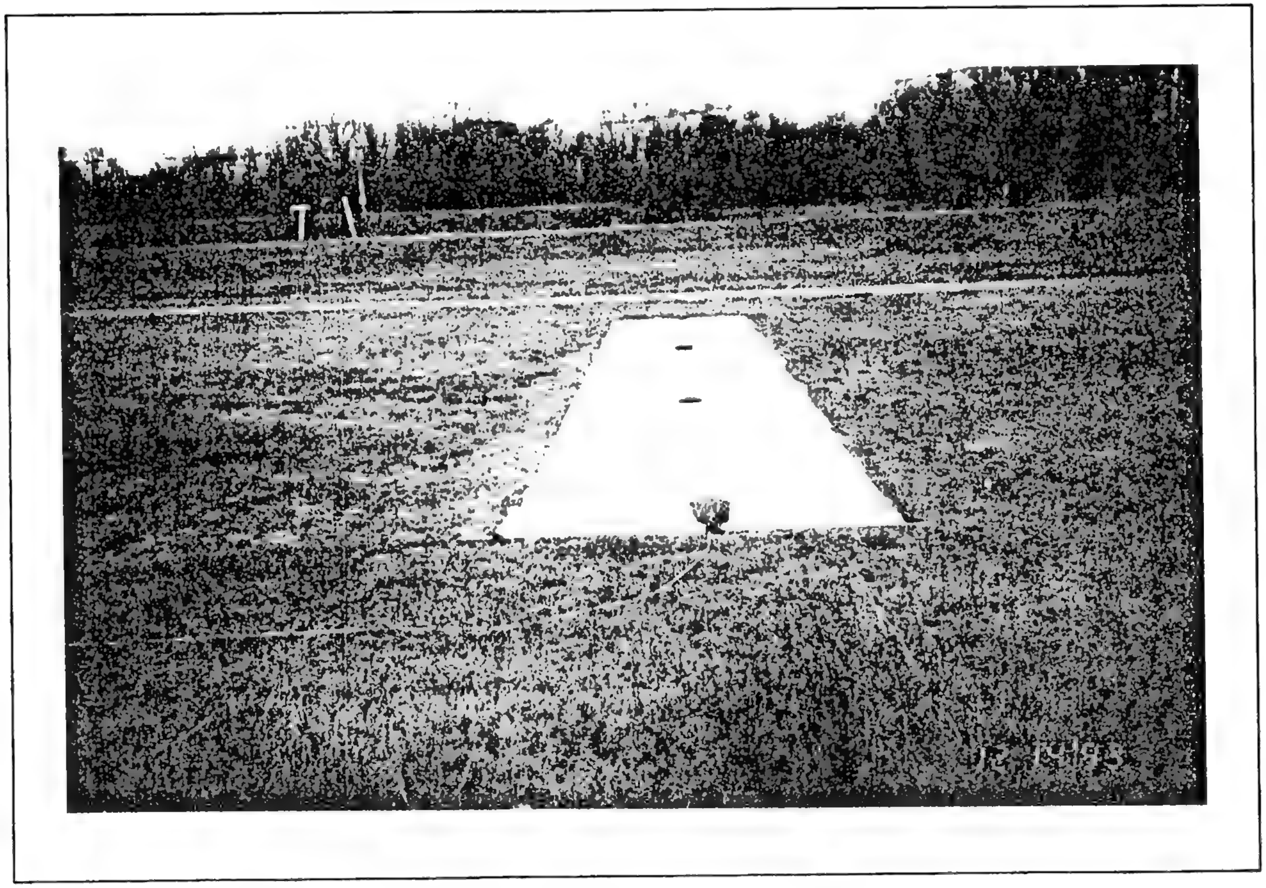


Figure 9. Portland cement concrete slab at BBTS

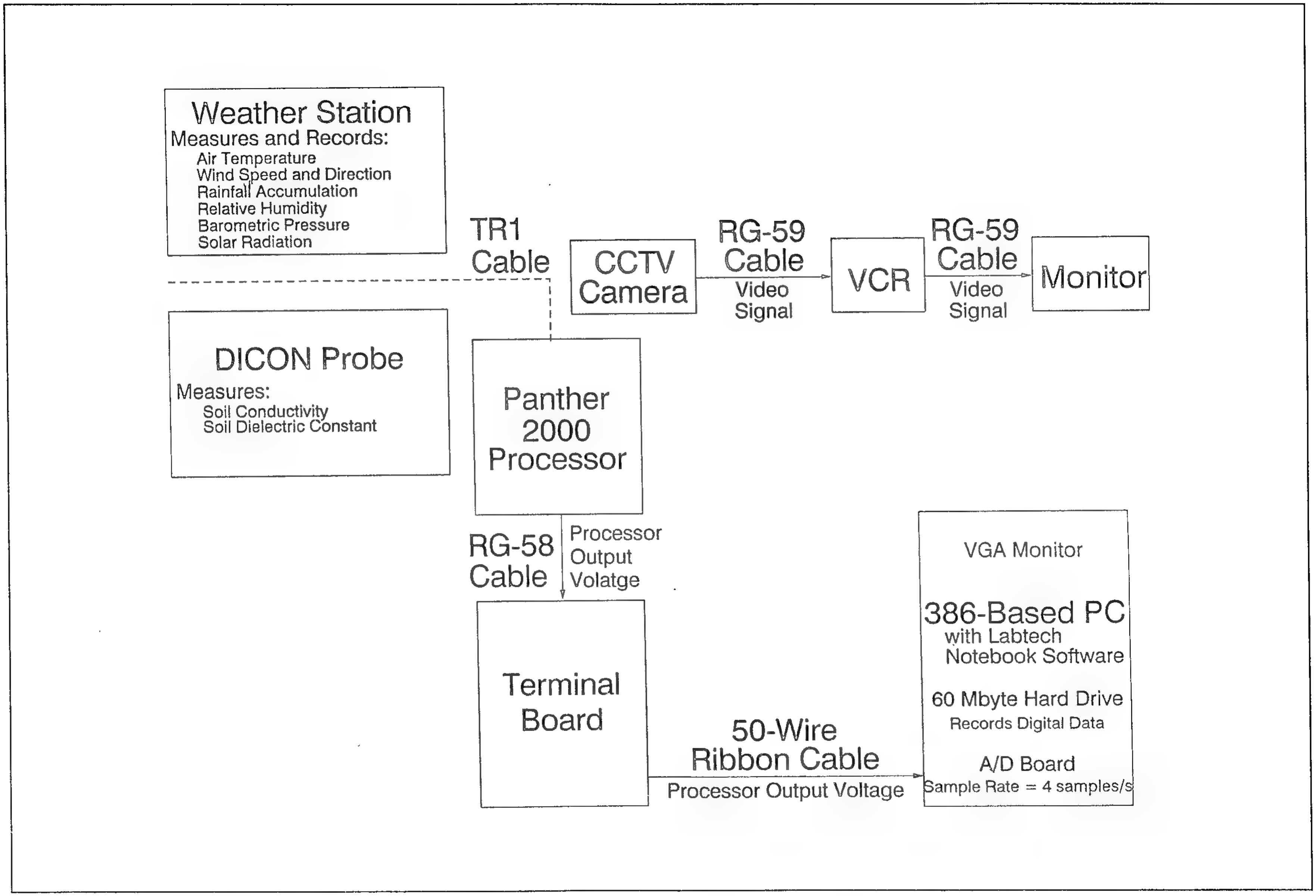


Figure 10. Block diagram of test equipment

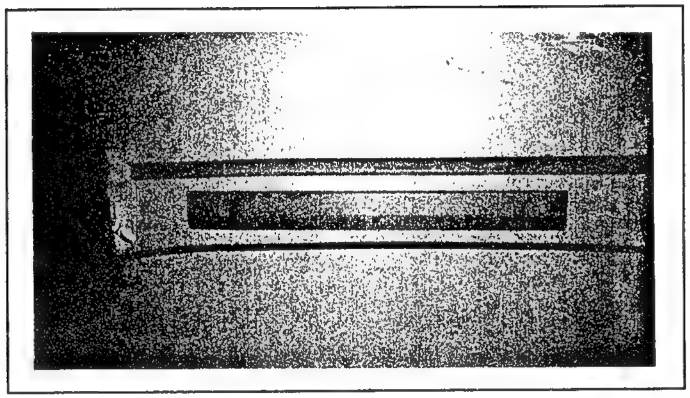


Figure 11. SPSC cable (top) and TR1 cable (bottom)

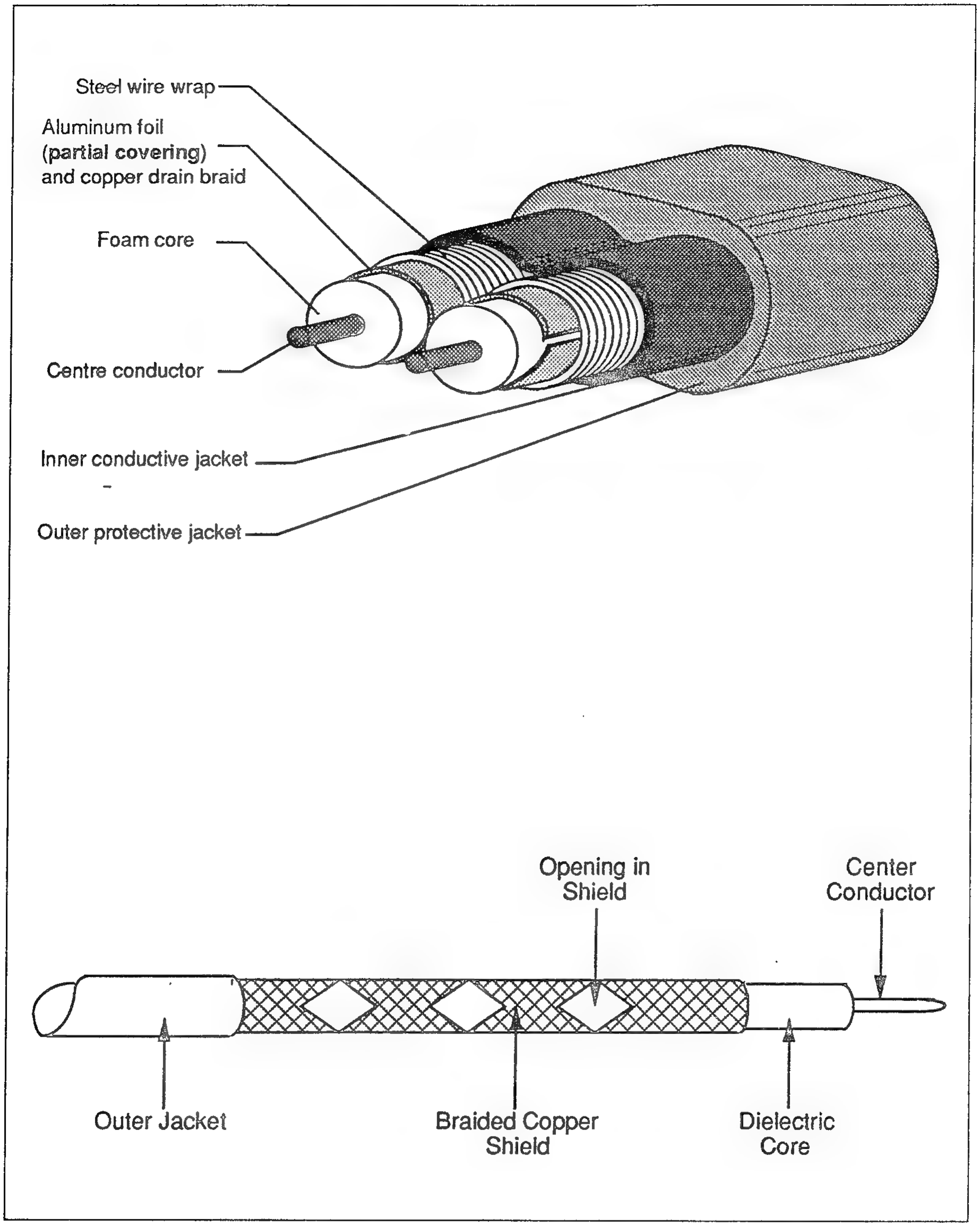


Figure 12. Schematic of the TR1 cable (top) and the SPCS cable (bottom)

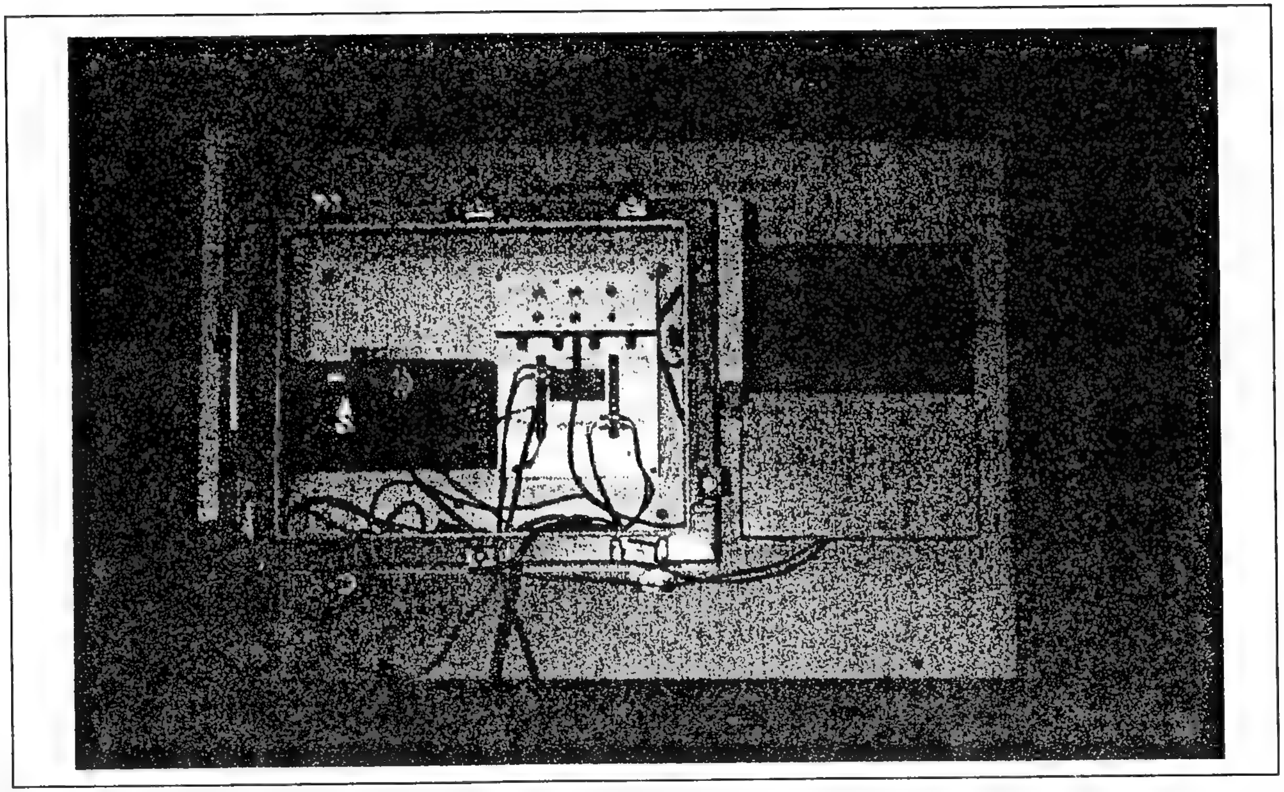


Figure 13. TM3-3T (left) and Panther 2000 (right) processors

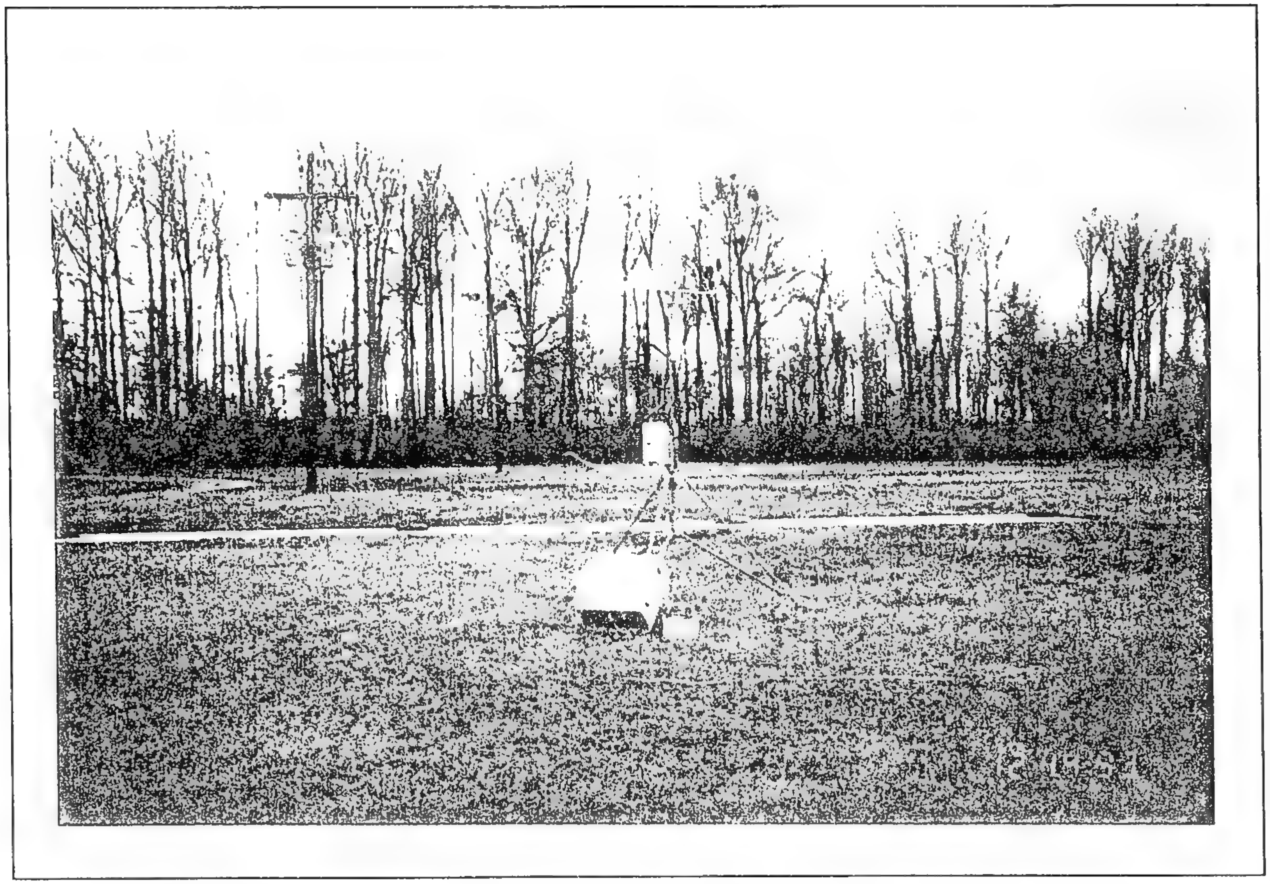


Figure 14. Portable weather station

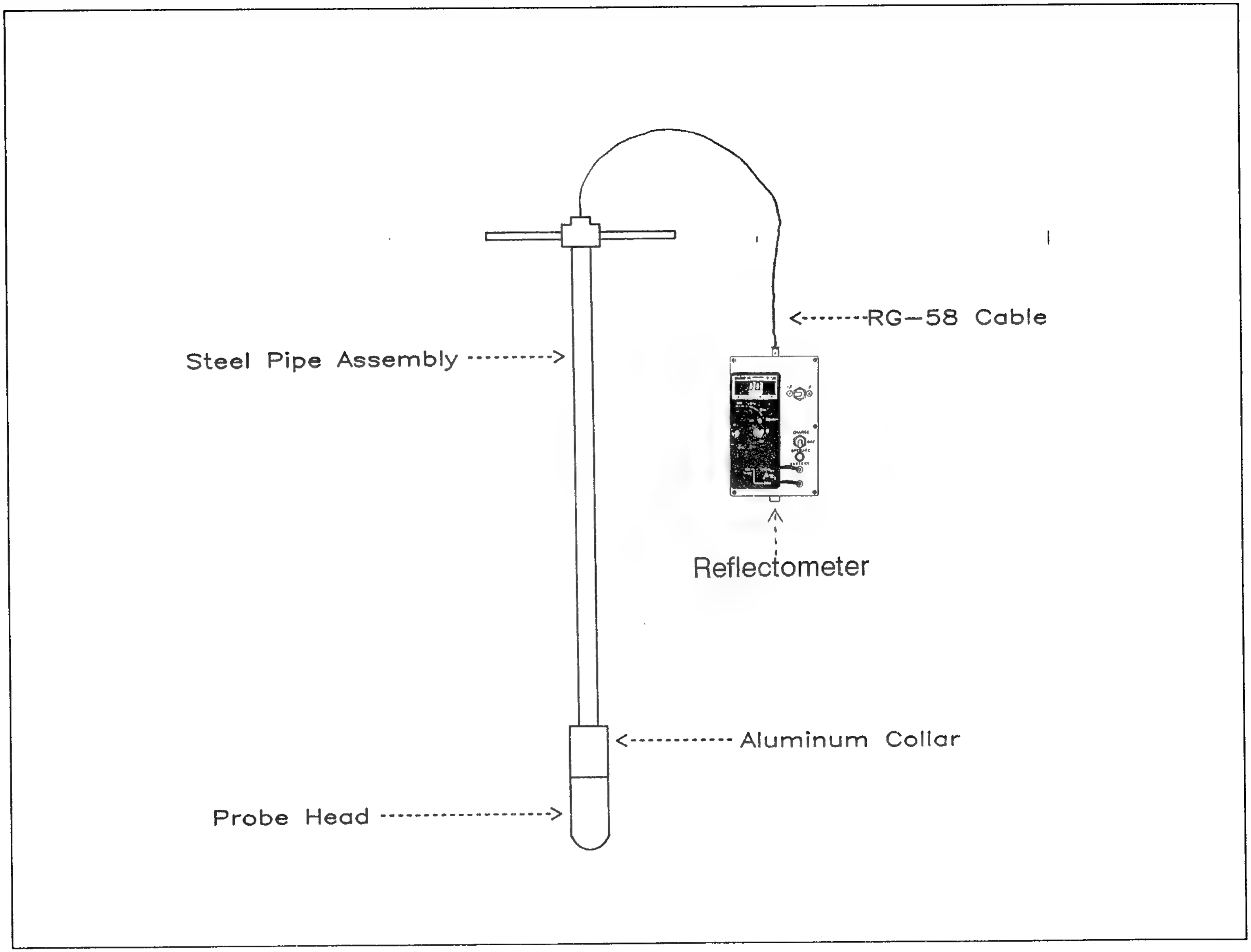


Figure 15. DICON probe

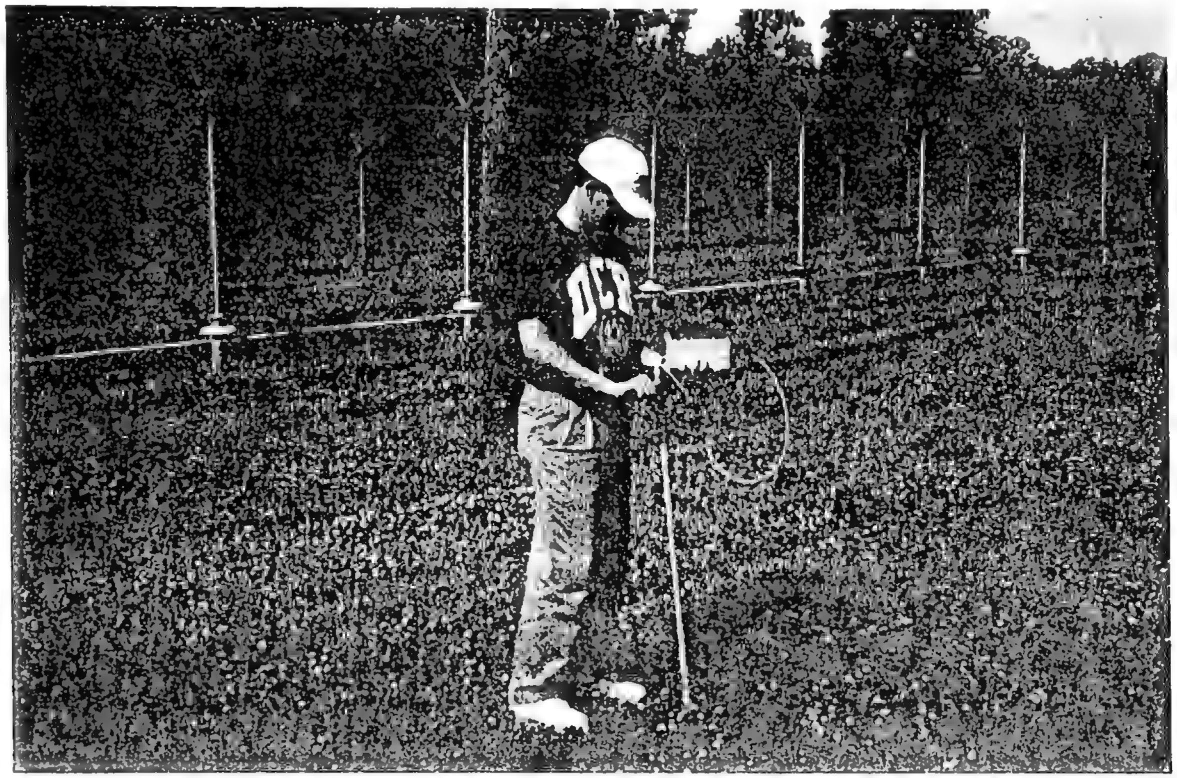


Figure 16. Obtaining field data with the DICON probe

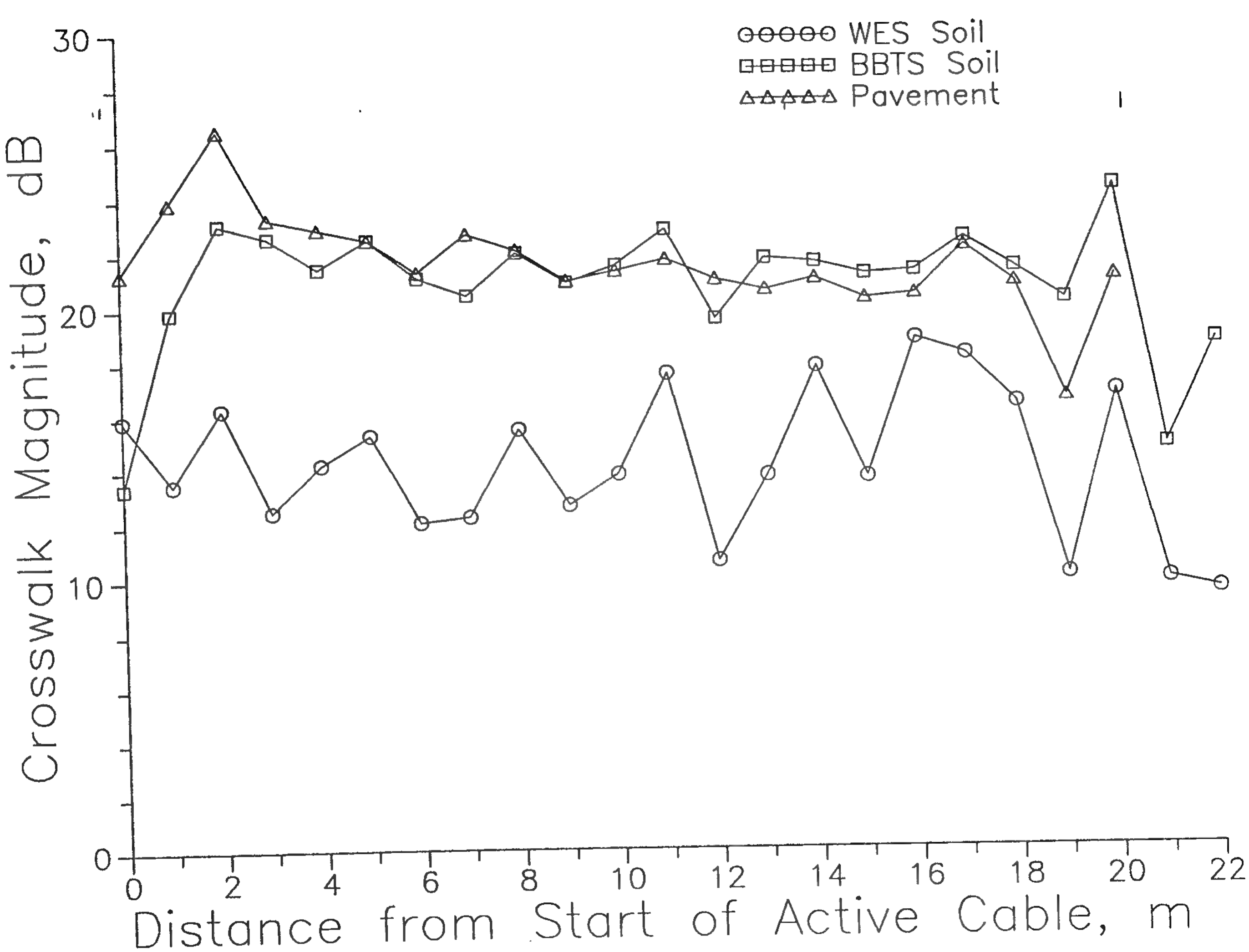


Figure 17. Target sensitivity of the TR1 cable deployed in WES soil, BBTS soil, and pavement

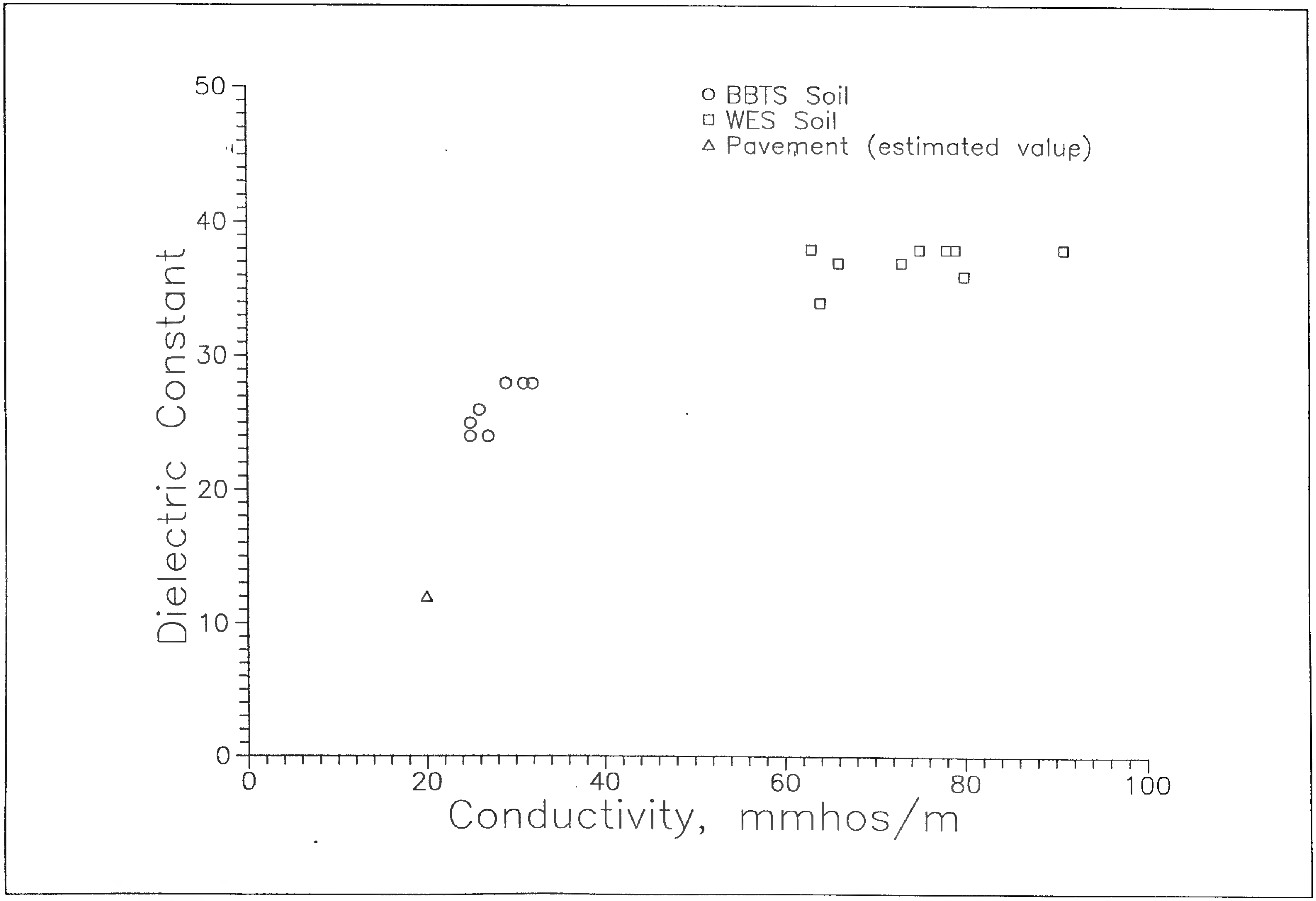


Figure 18. Electrical properties of WES soil, BBTS soil, and pavement

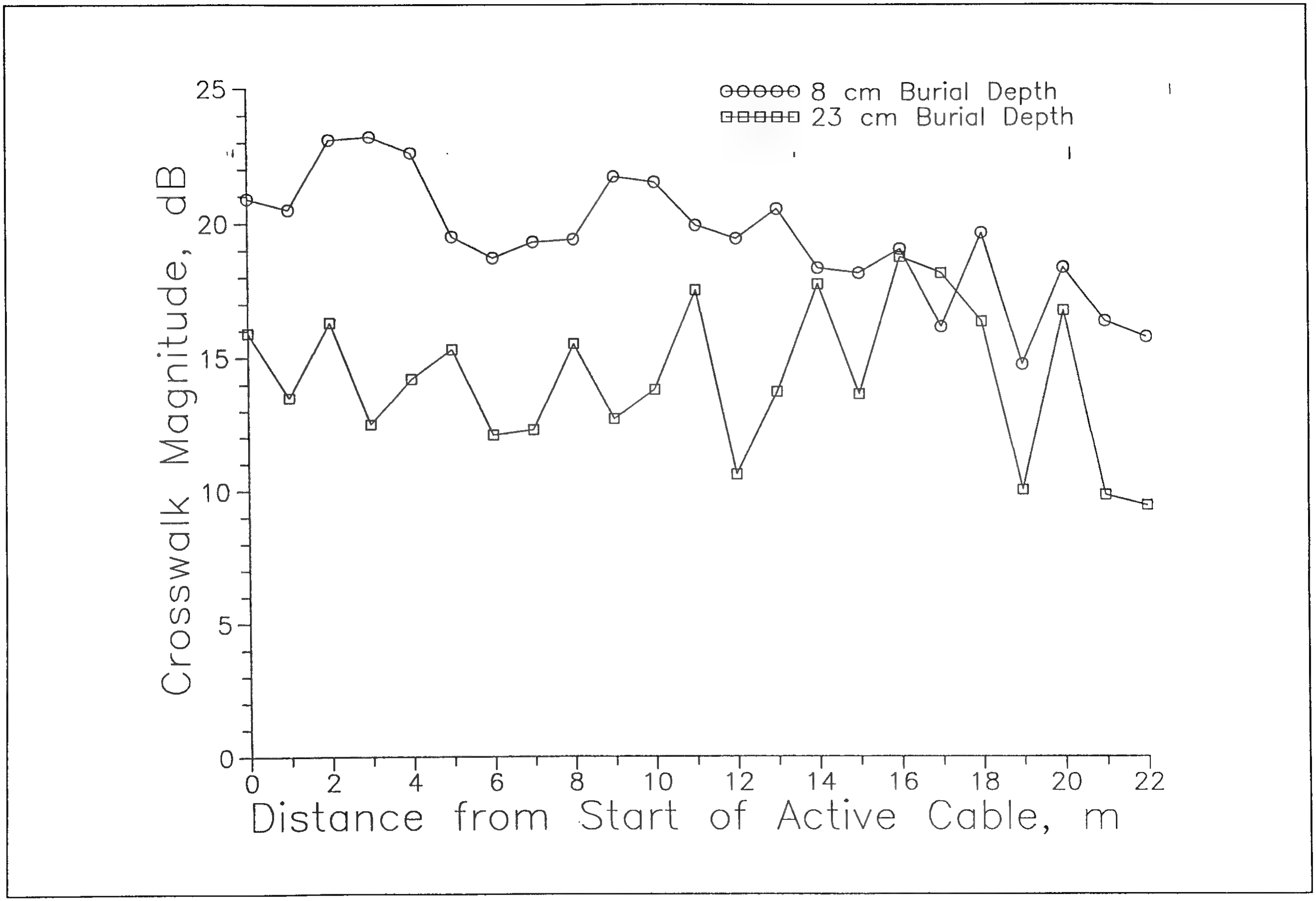


Figure 19. Target sensitivity of TR1 cable deployed at 8-cm and 23-cm depths in WES soil

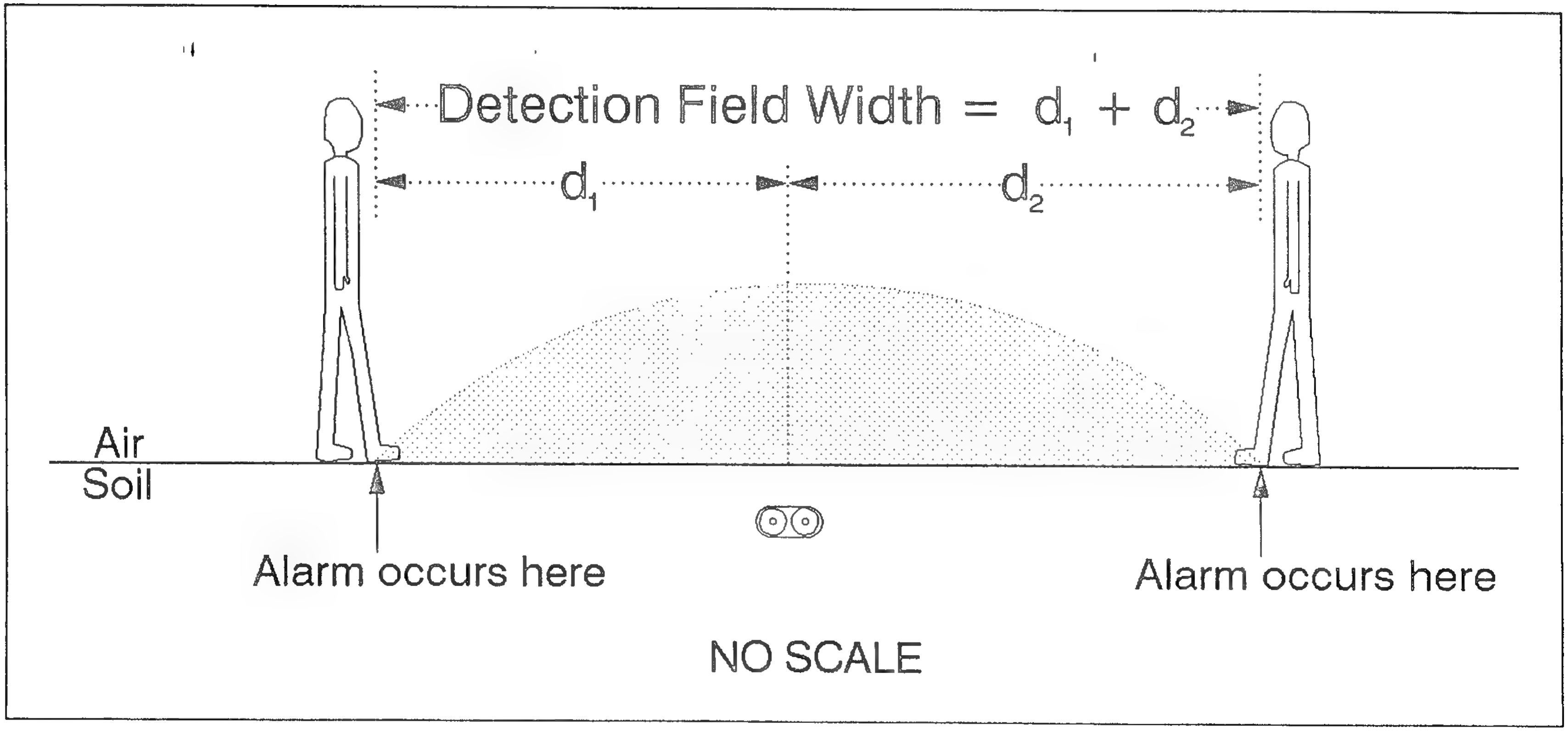


Figure 20. Procedure for measuring detection field width

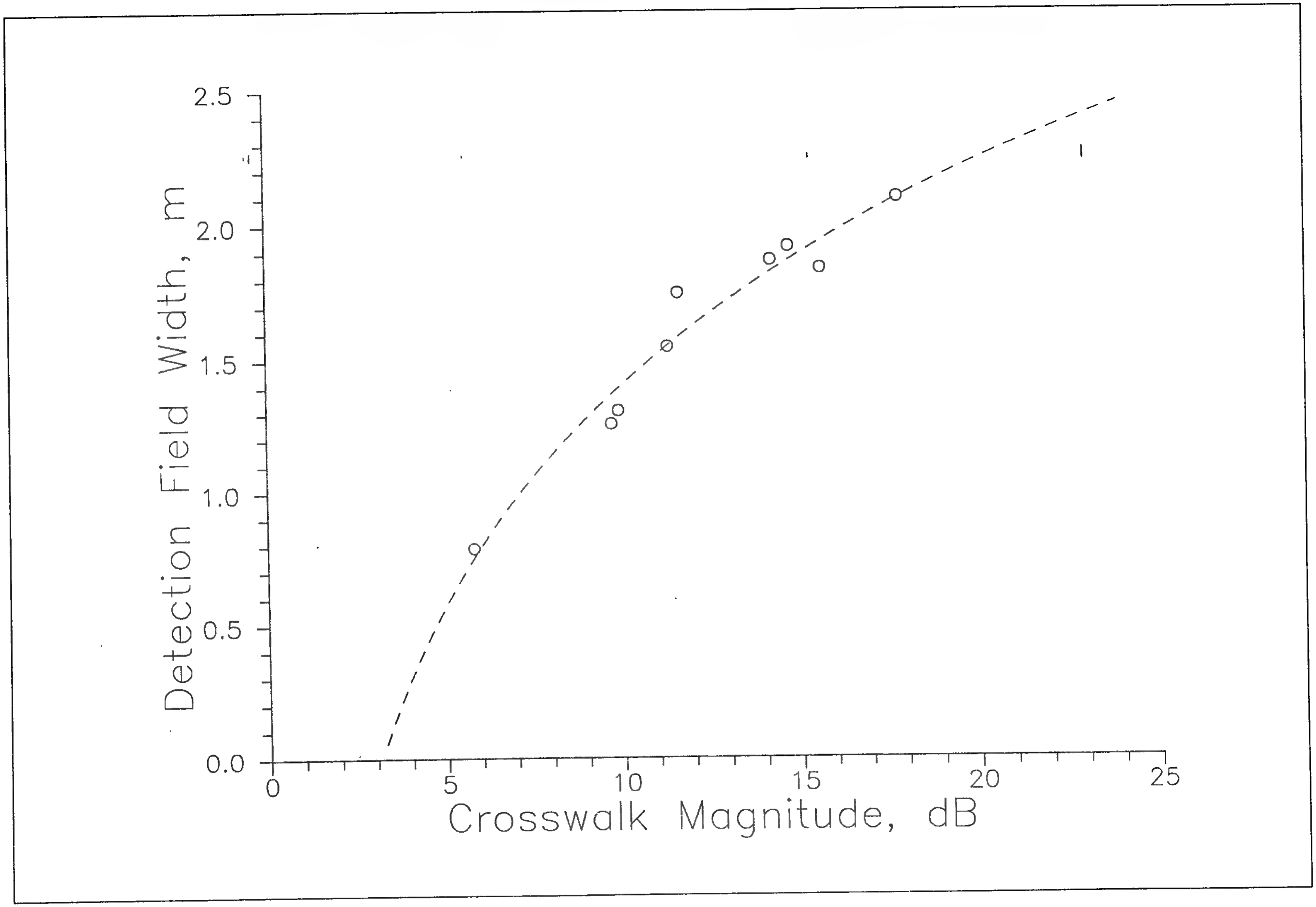


Figure 21. Detection field width data for the TR1 cable

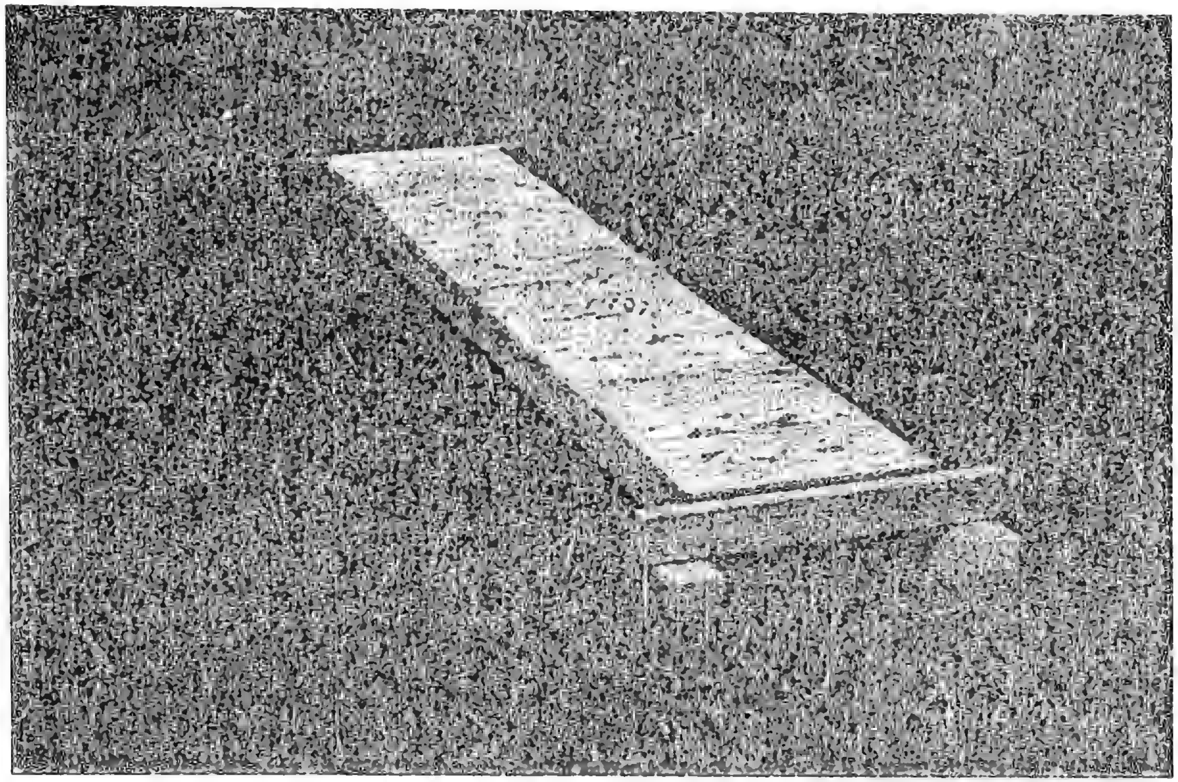


Figure 22. Wooden platform used to measure detection field height

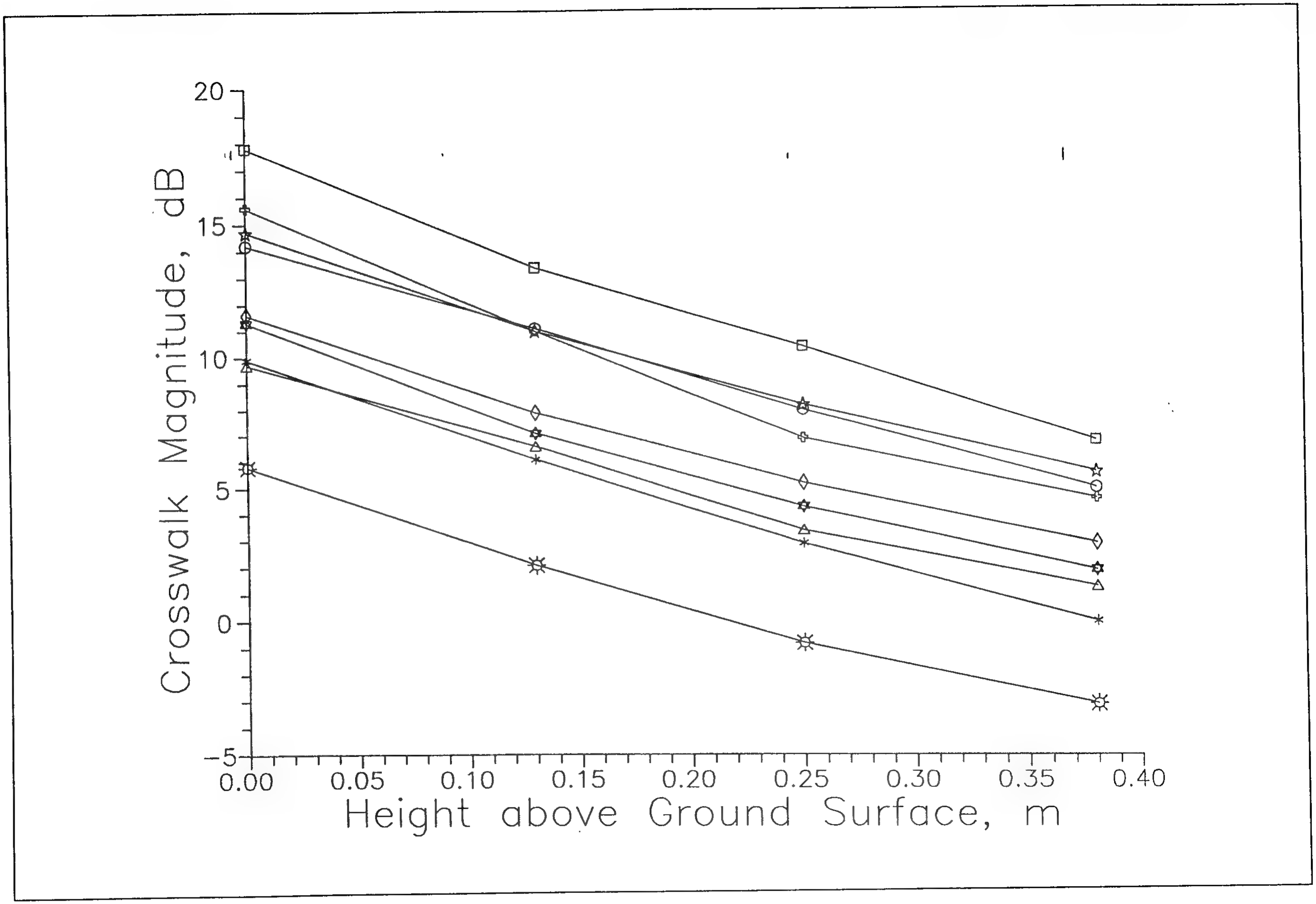


Figure 23. Detection field height data for the TR1 cable

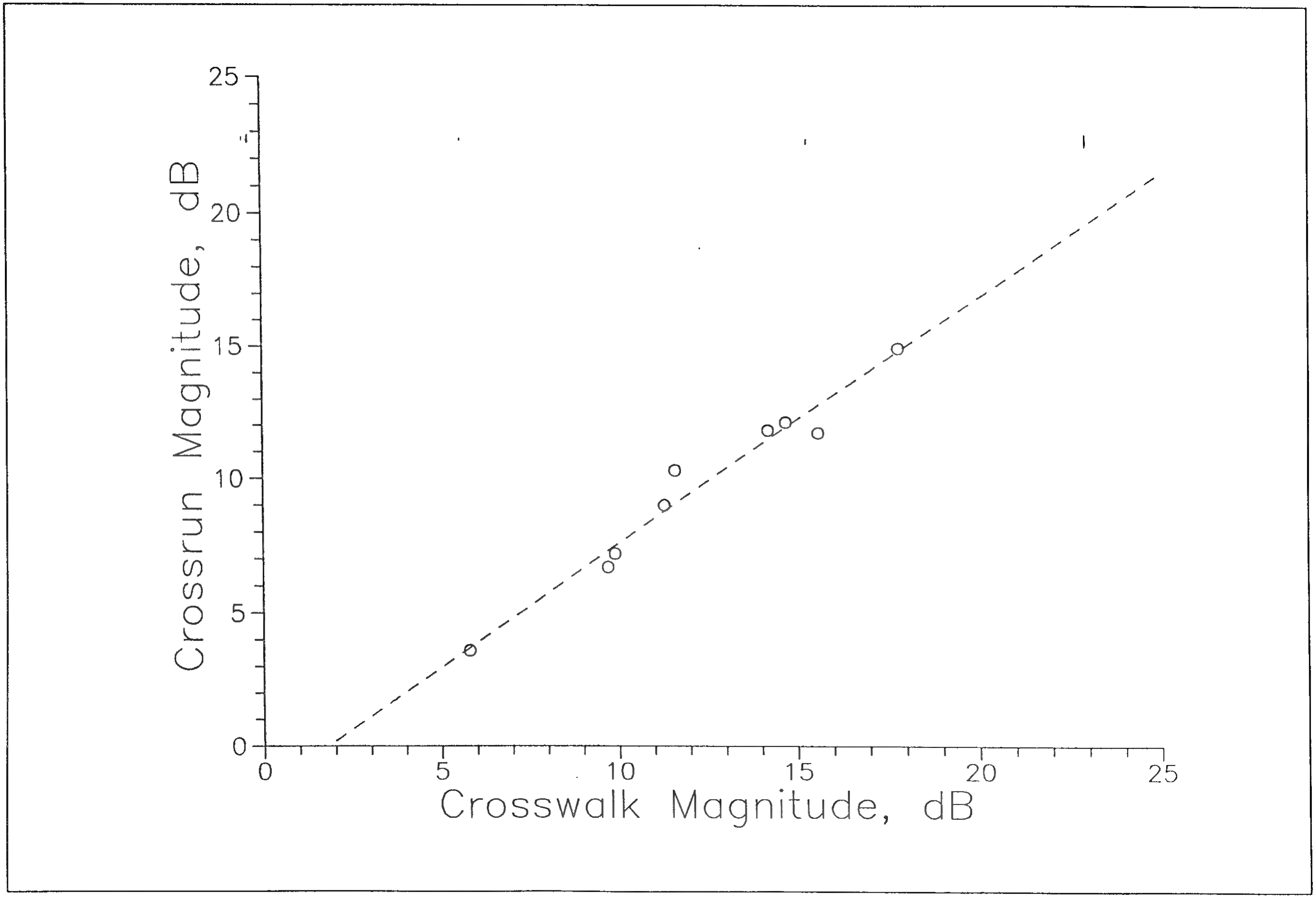


Figure 24. Target speed test data for the TR1 cable

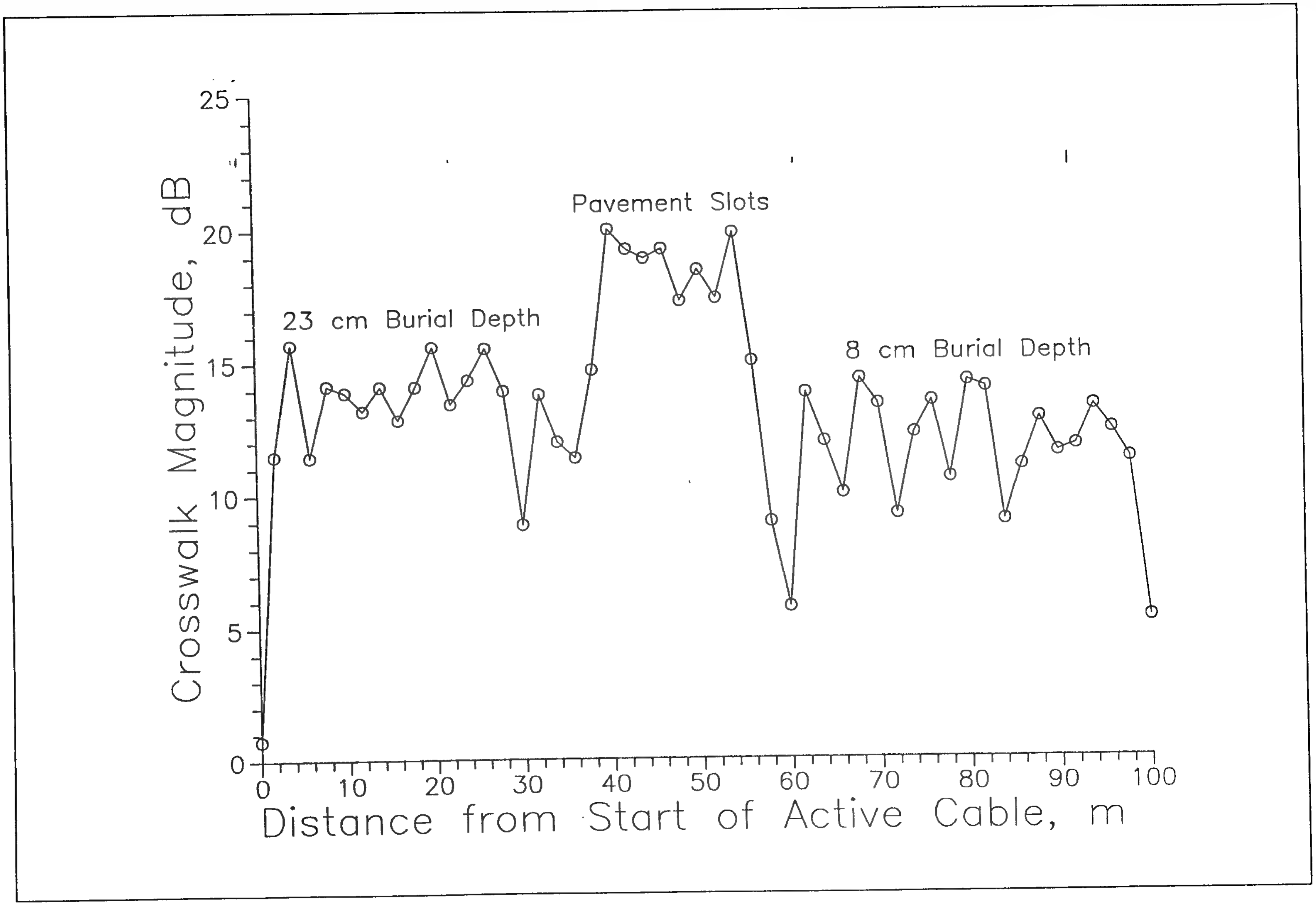


Figure 25. Target sensitivity of the TR1 cable deployed at the BBTS

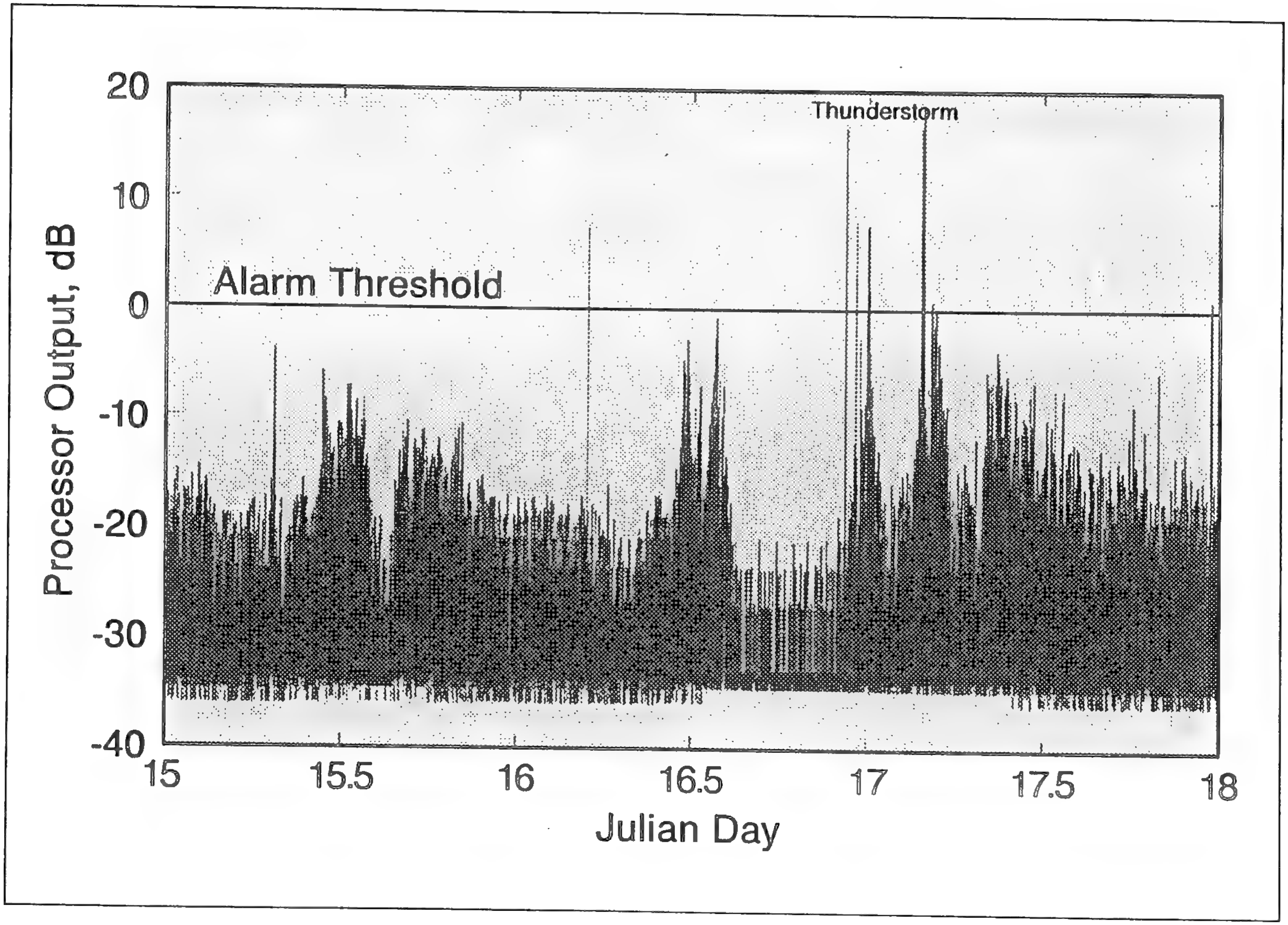


Figure 26. Processor output during the 72-hr monitoring period at the BBTS

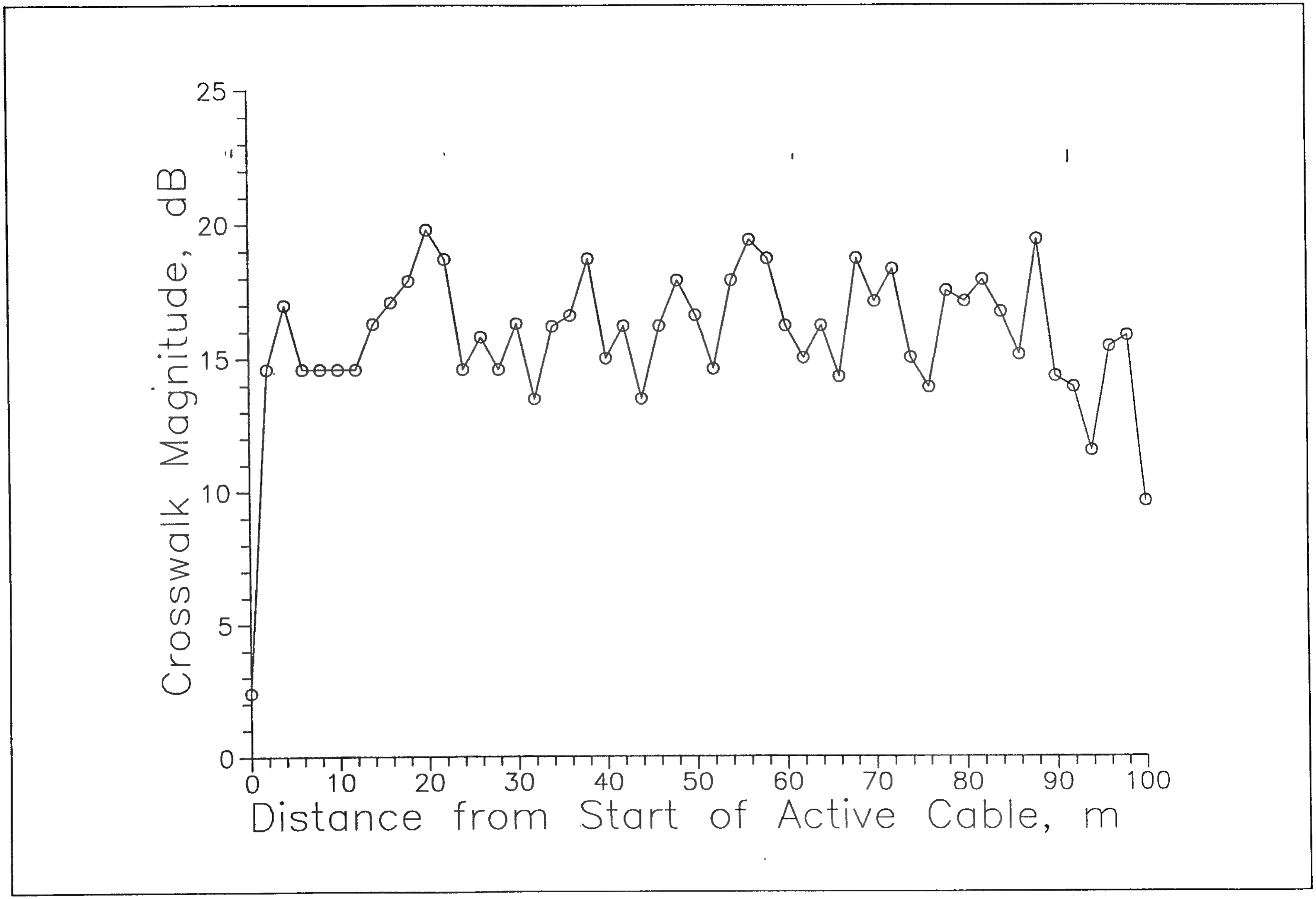


Figure 27. Target sensitivity of the TR1 cable deployed at the WES site

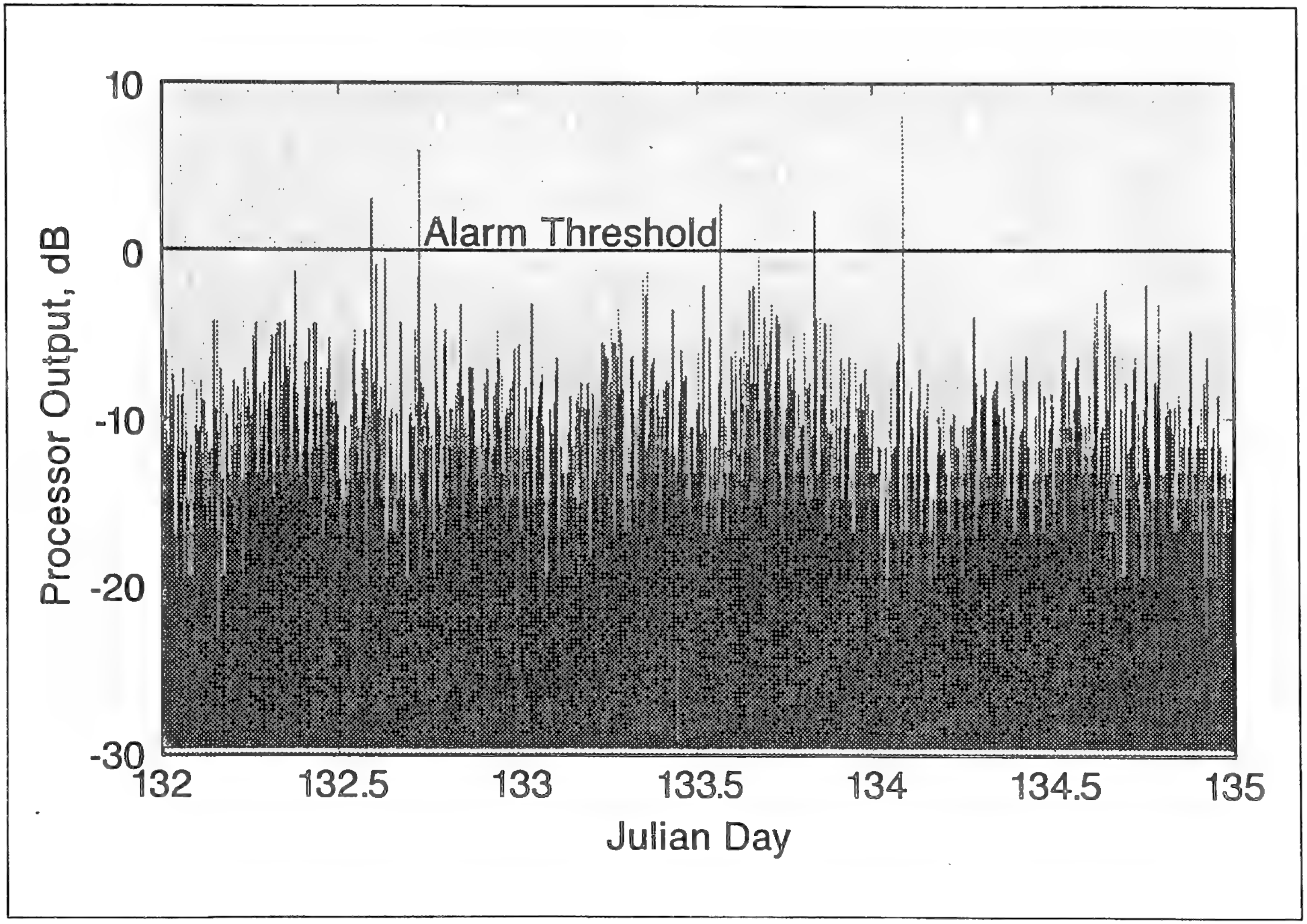


Figure 28. Processor output during the 72-hr monitoring period at the WES site

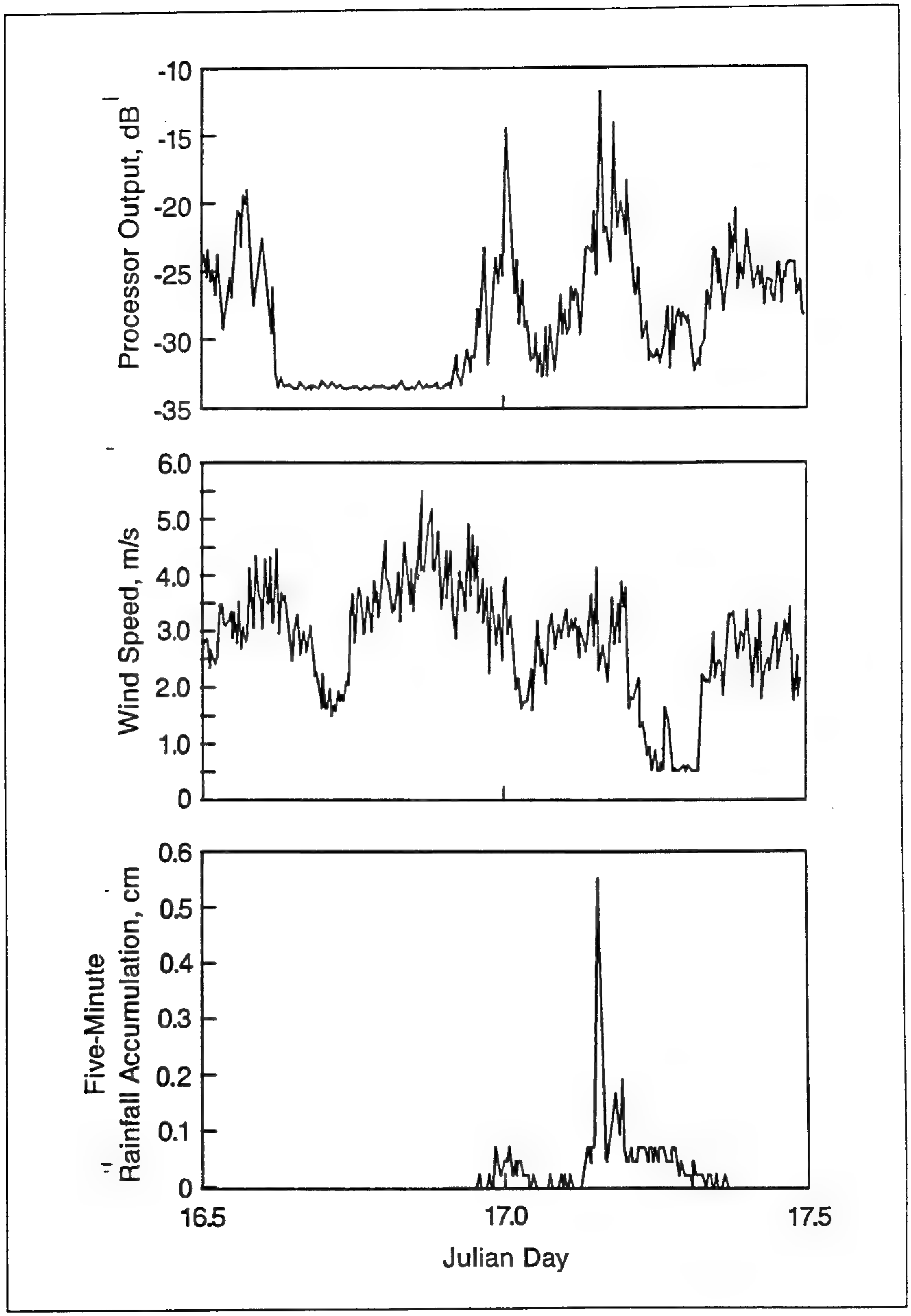


Figure 29. Processor output, wind speed, and rainfall during one 24-hr period at the BBTS

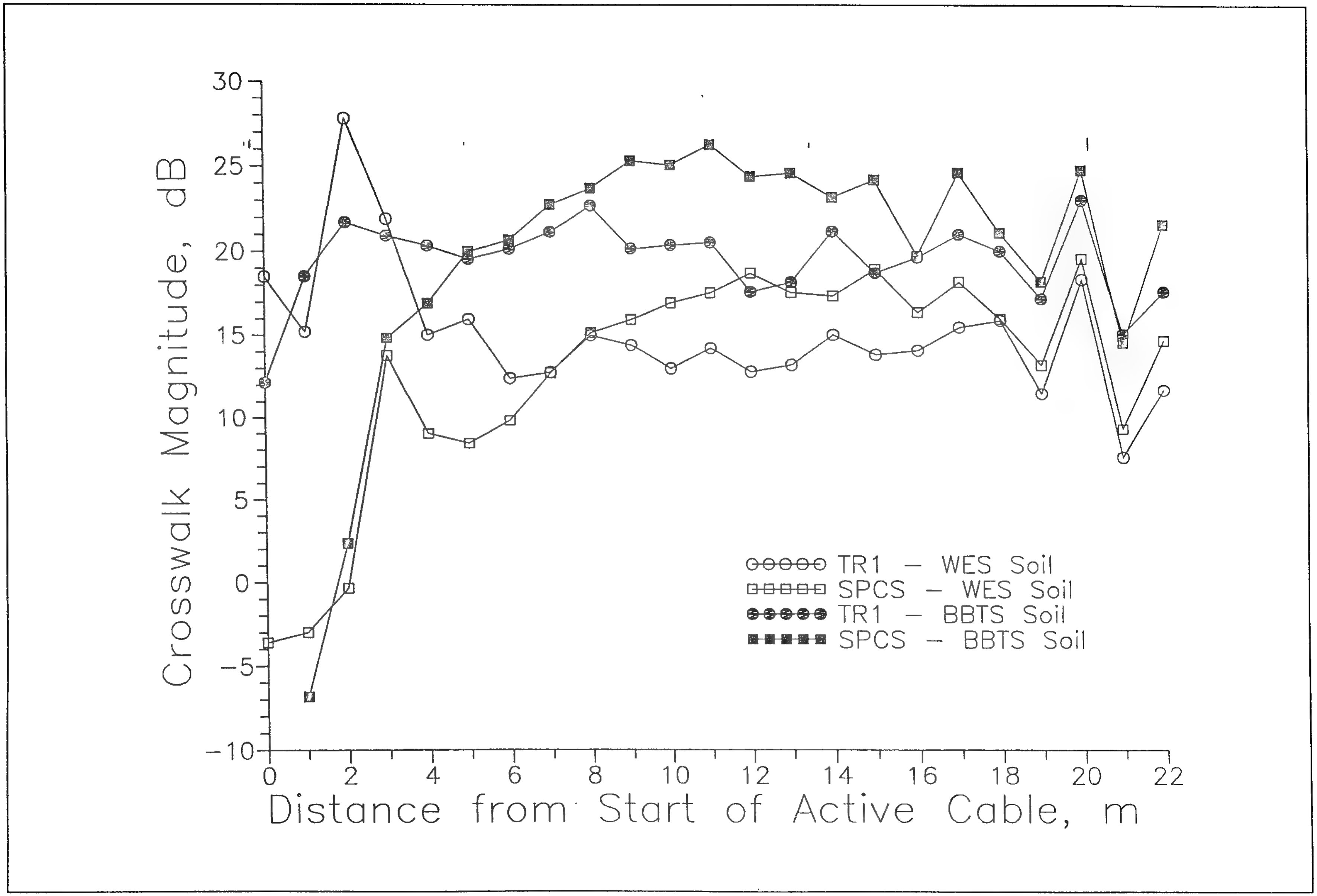


Figure 30. Target sensitivity of the TR1 and SPCS cables deployed in WES soil and BBTS soil

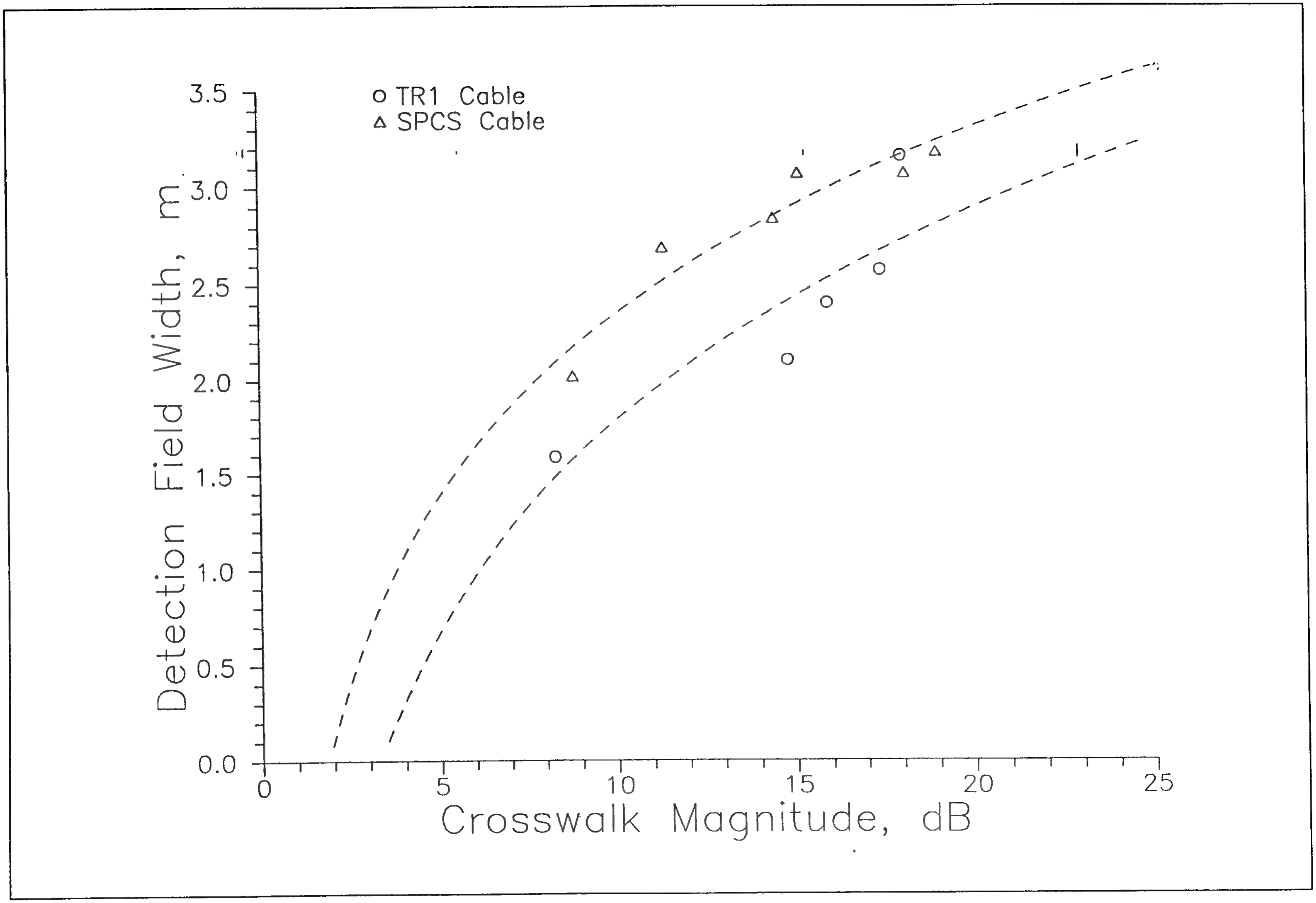


Figure 31. Detection field width data for the TR1 and SPCS cables

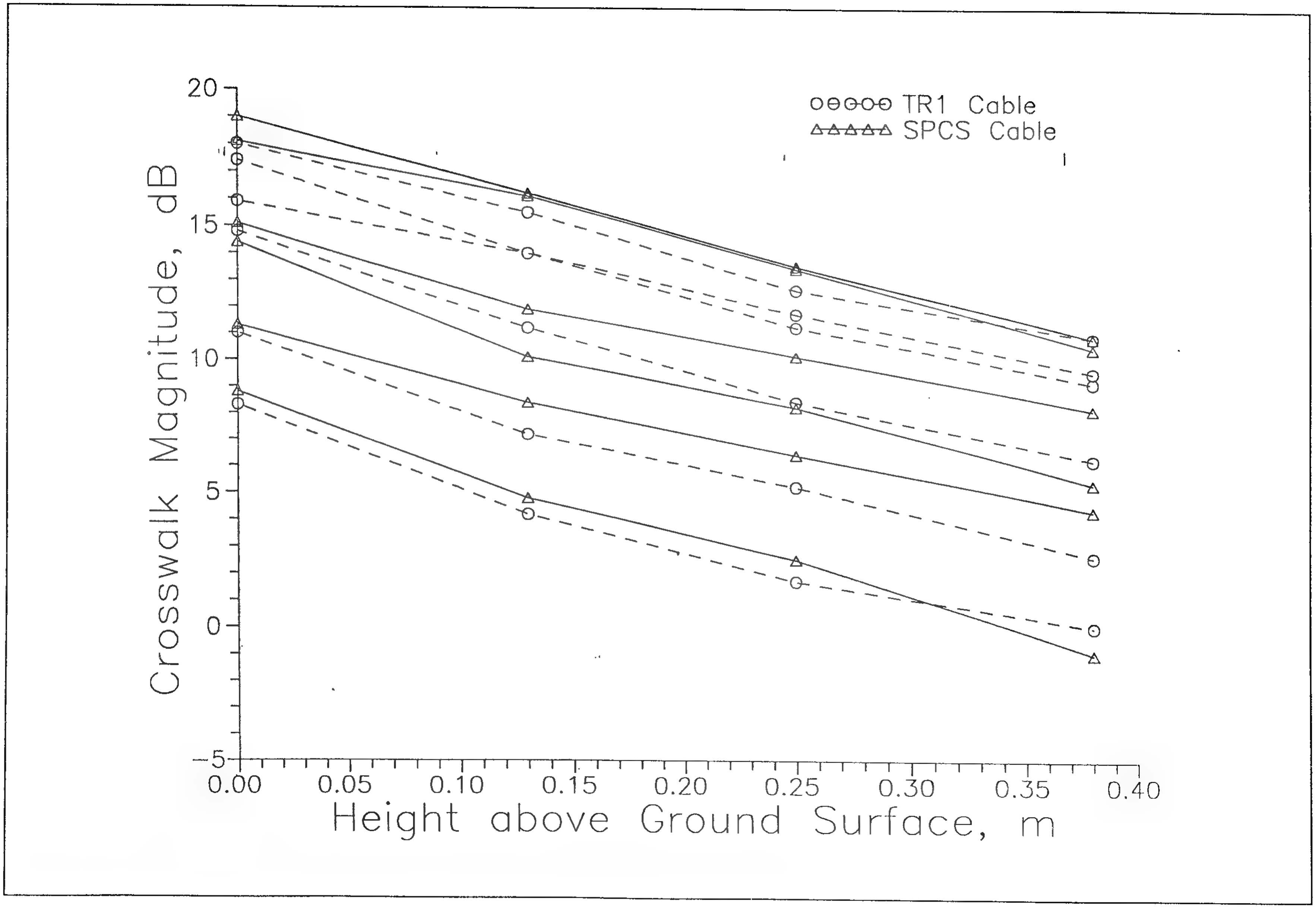


Figure 32. Detection field height data for the TR1 and SPCS cables

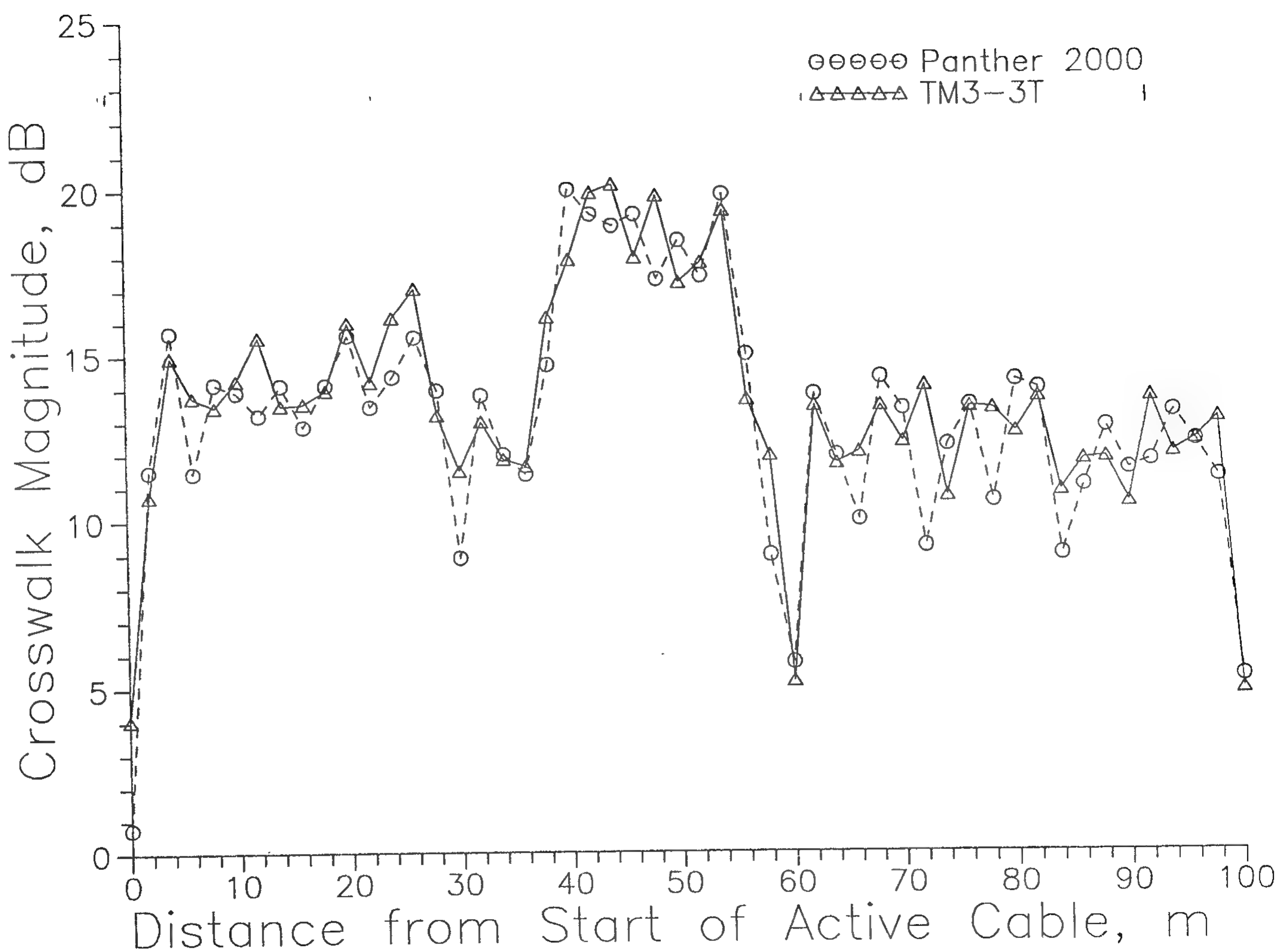


Figure 33. Target sensitivity of the TR1 cable connected to the Panther 2000 and TM3-3T processors

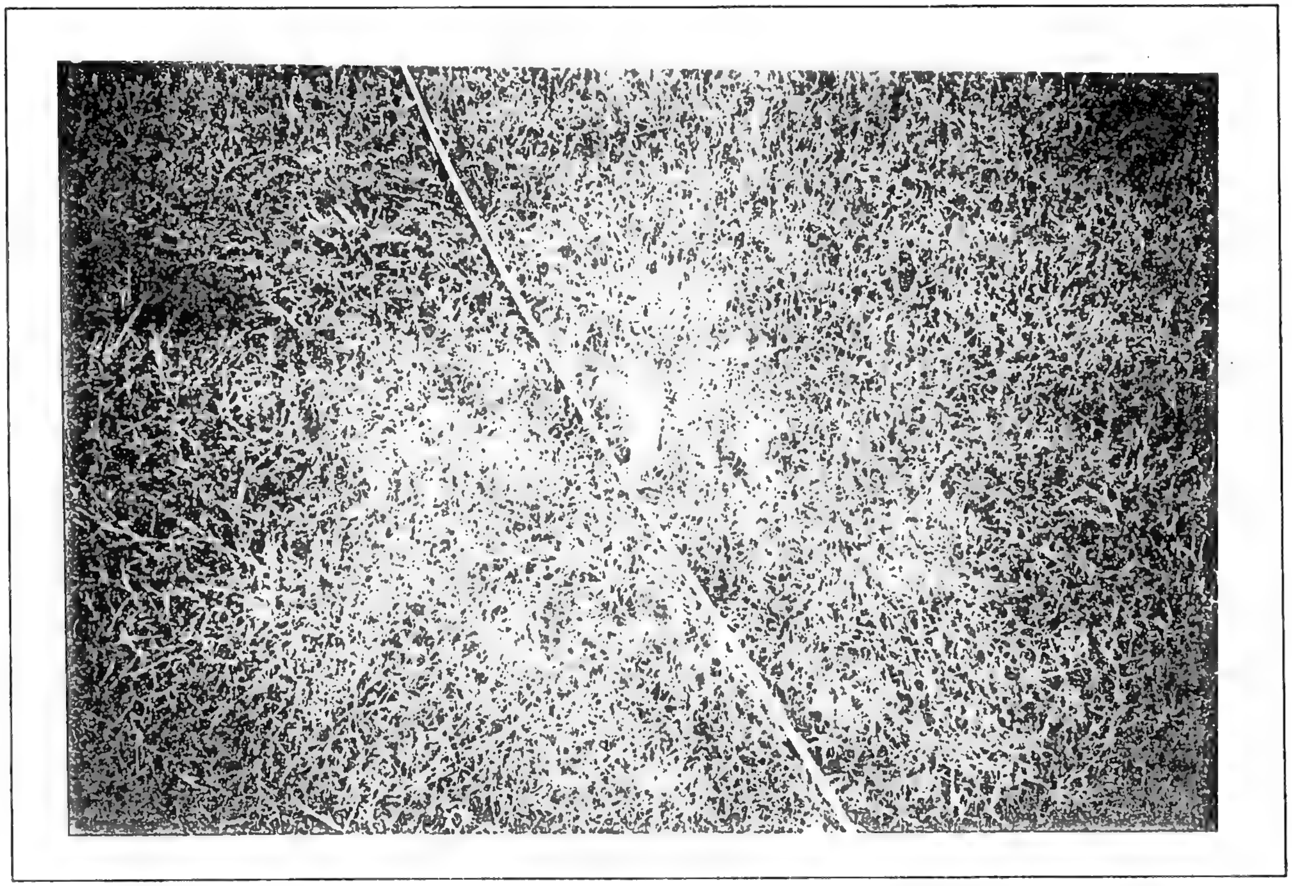


Figure 34. TR1 cable deployed on the ground surface

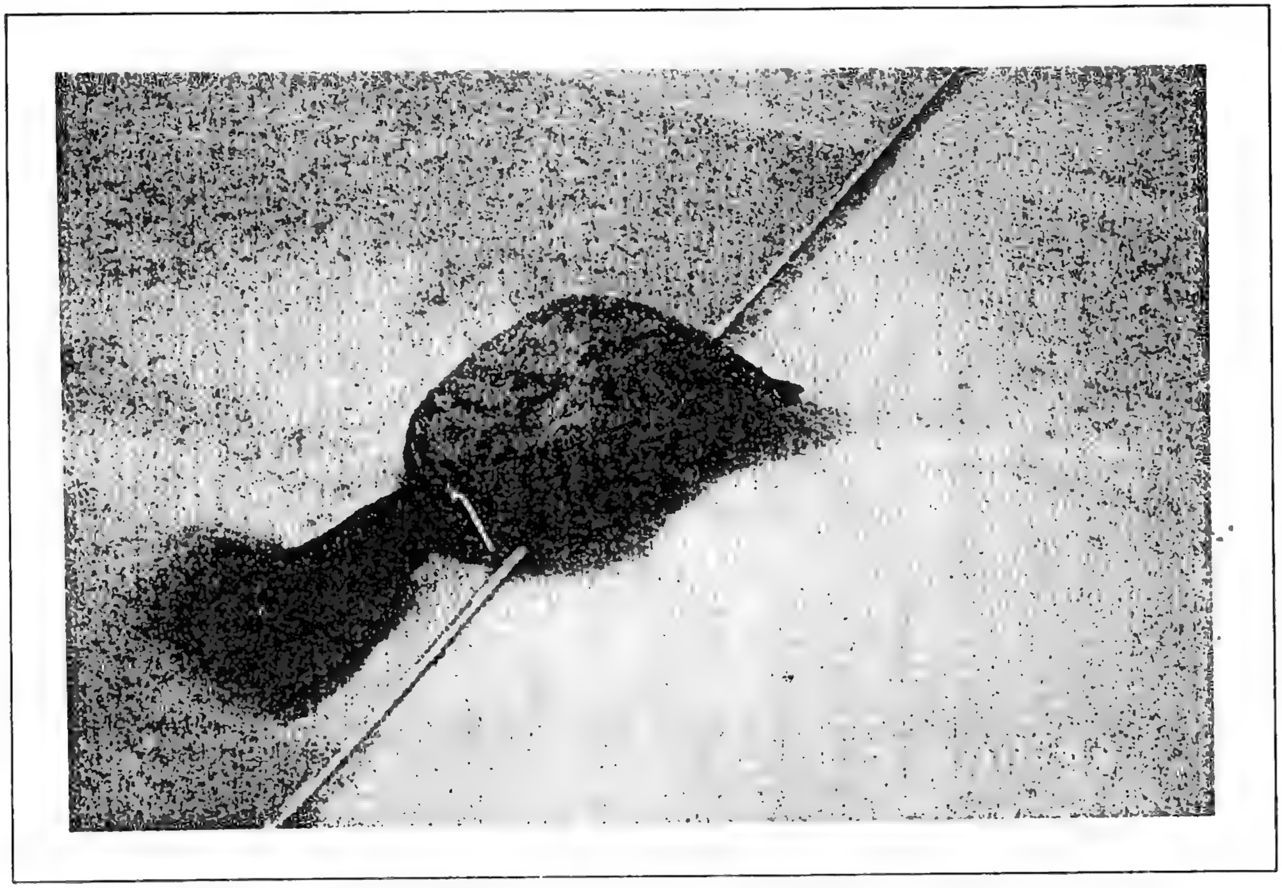


Figure 35. TR1 cable deployed on the pavement surface

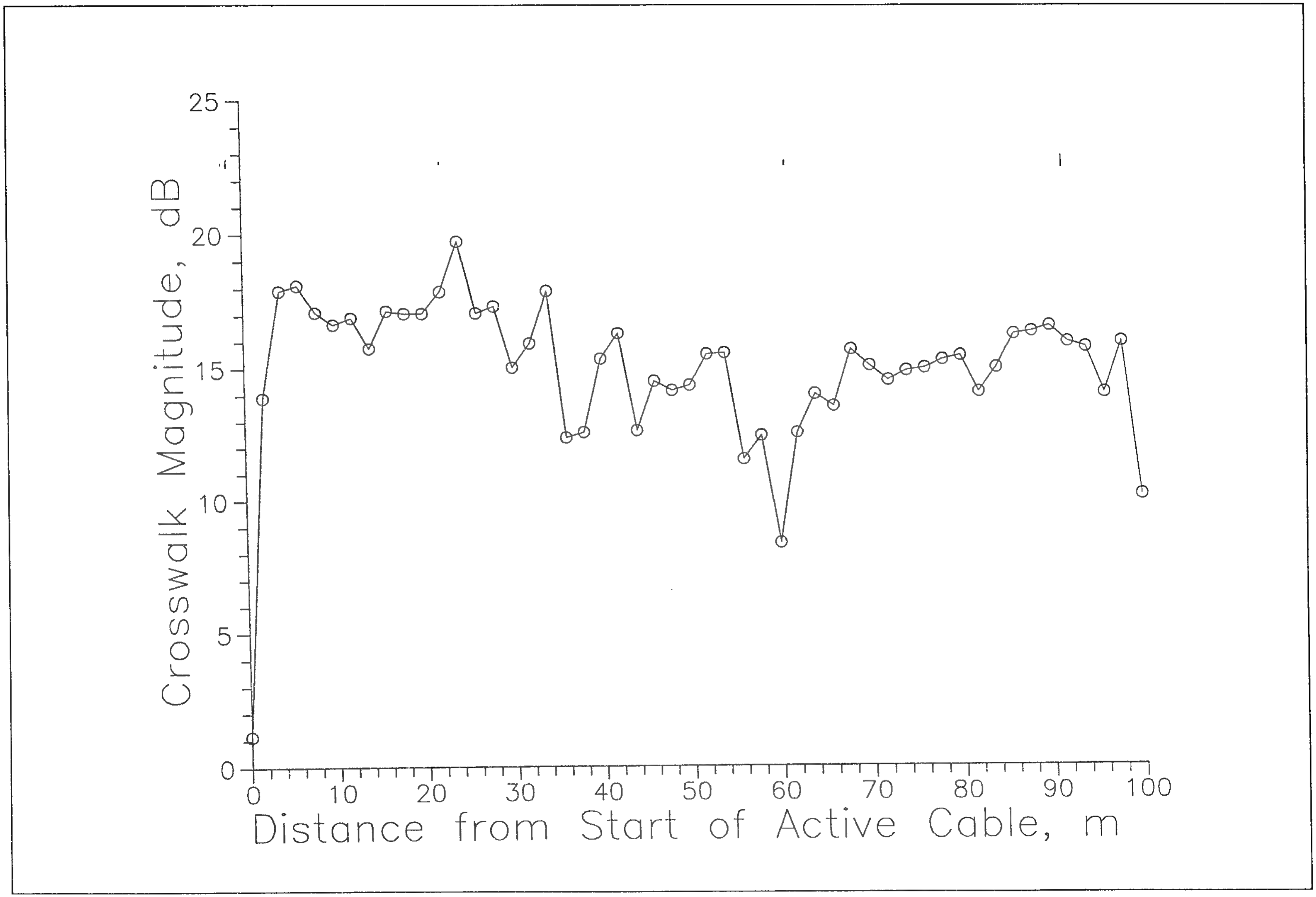


Figure 36. Target sensitivity of the TR1 cable deployed on the surface at the BBTS

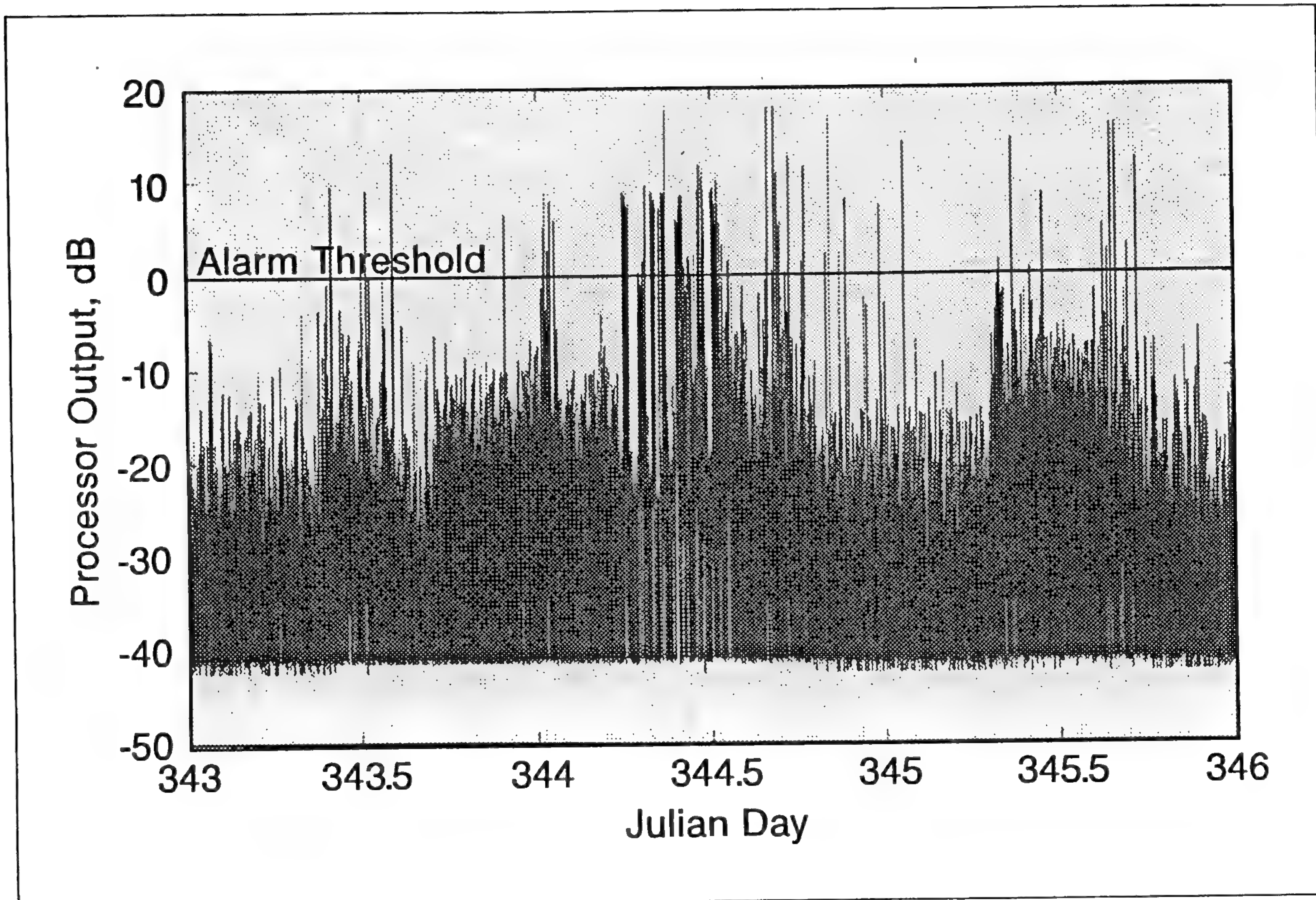


Figure 37. Processor output for the 72-hr monitoring period at the BBTS with the TR1 cable deployed on the surface

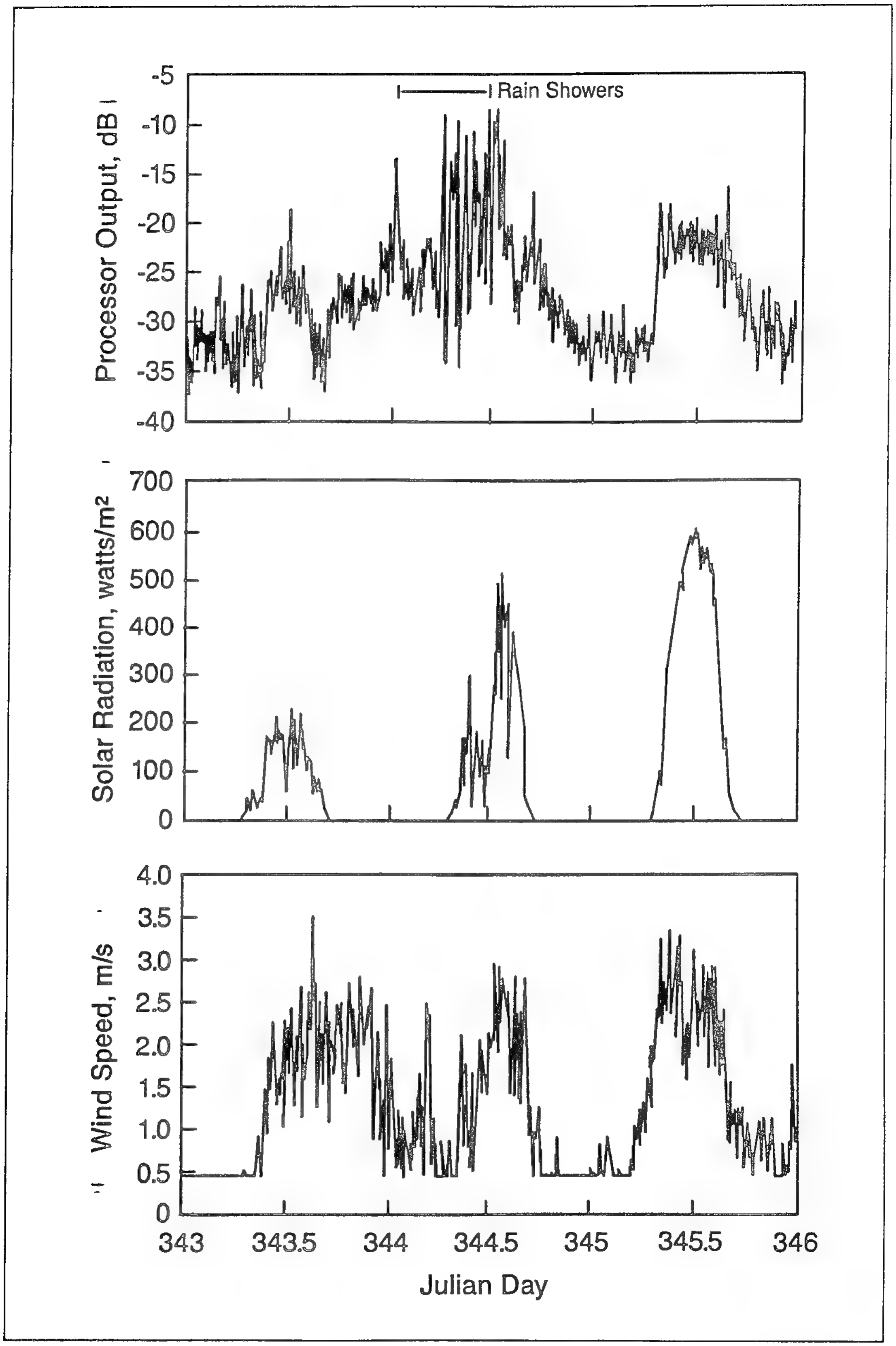
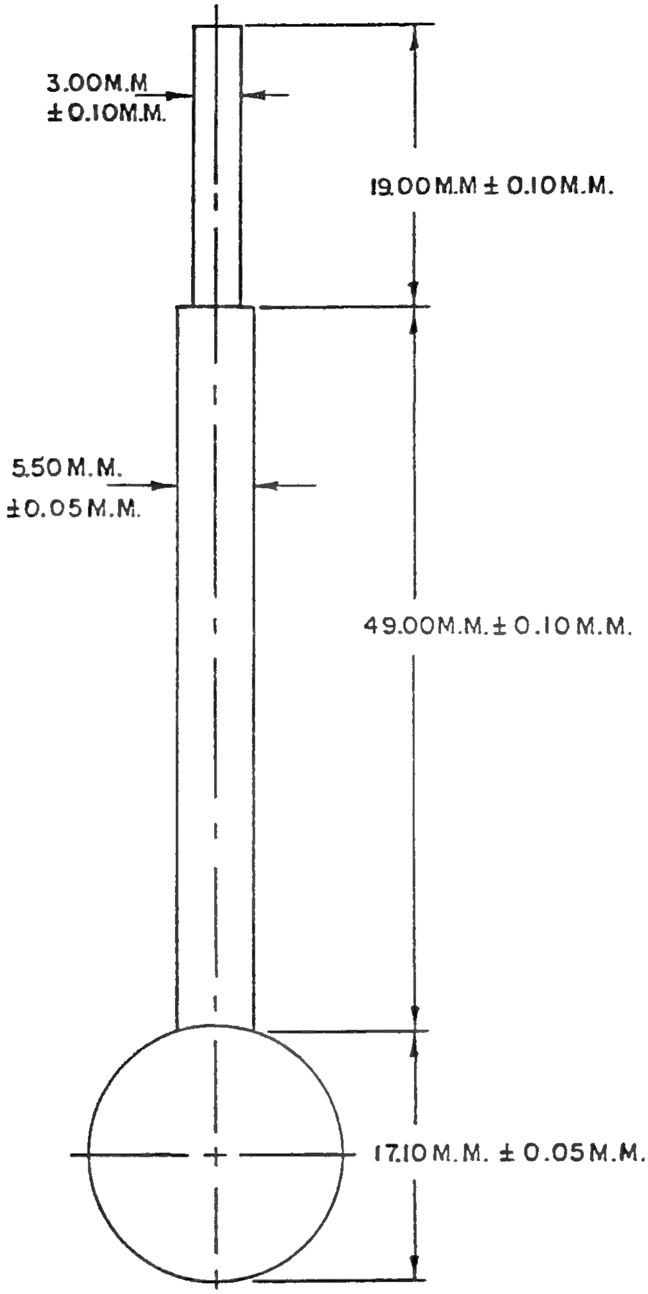


Figure 38. Processor output, solar radiation, and wind speed measured during the 72-hr monitoring period at the BBTS with the TR1 cable deployed on the surface



Notes:
Tool Weight: 27.50 grams ± 0.10 grams.
Tool Weight on Specimen: 75.00 grams ± 0.01 grams.

Figure 39. Ball penetrometer tool

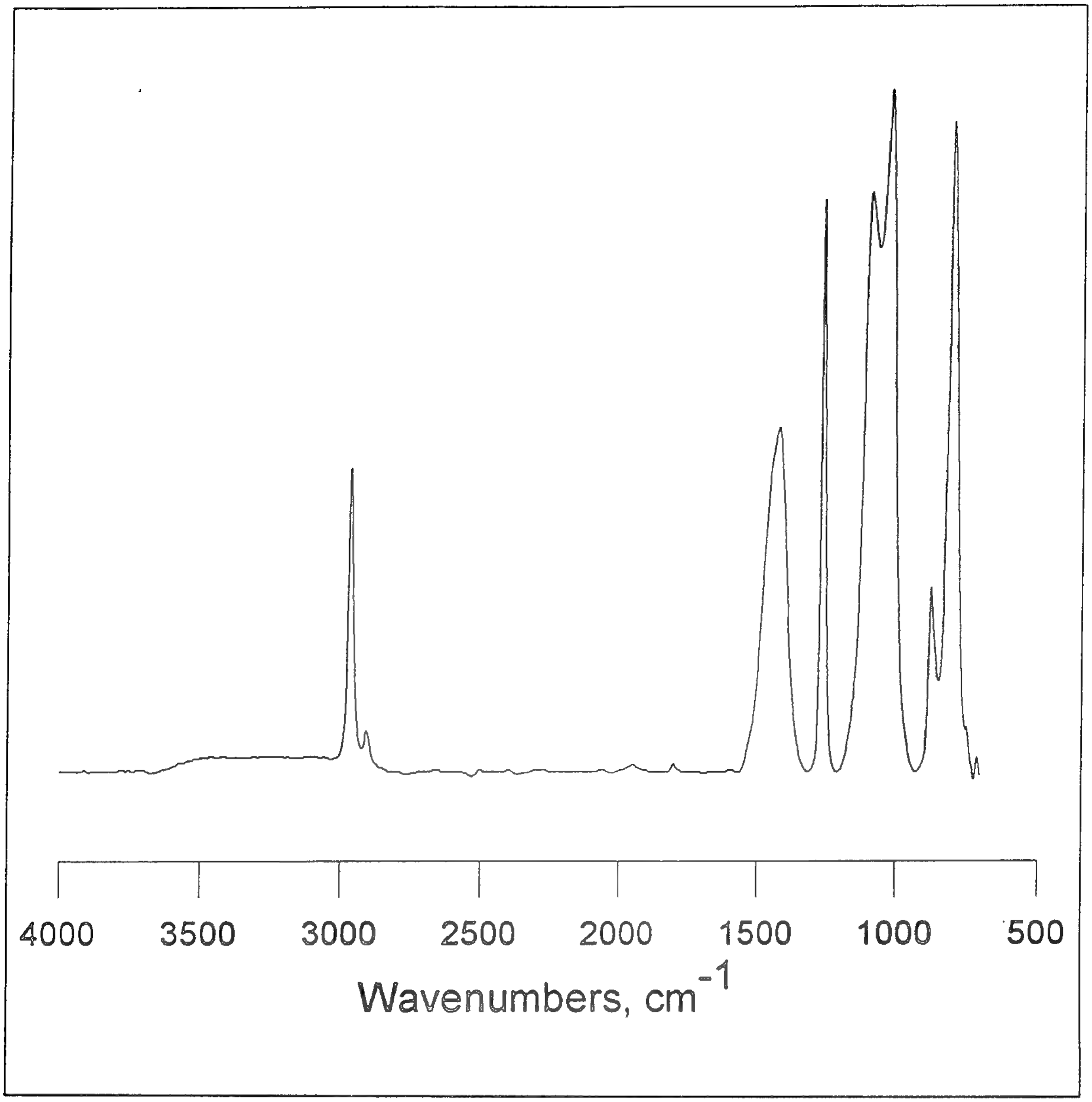


Figure 40. Typical FTIR-ATR spectra

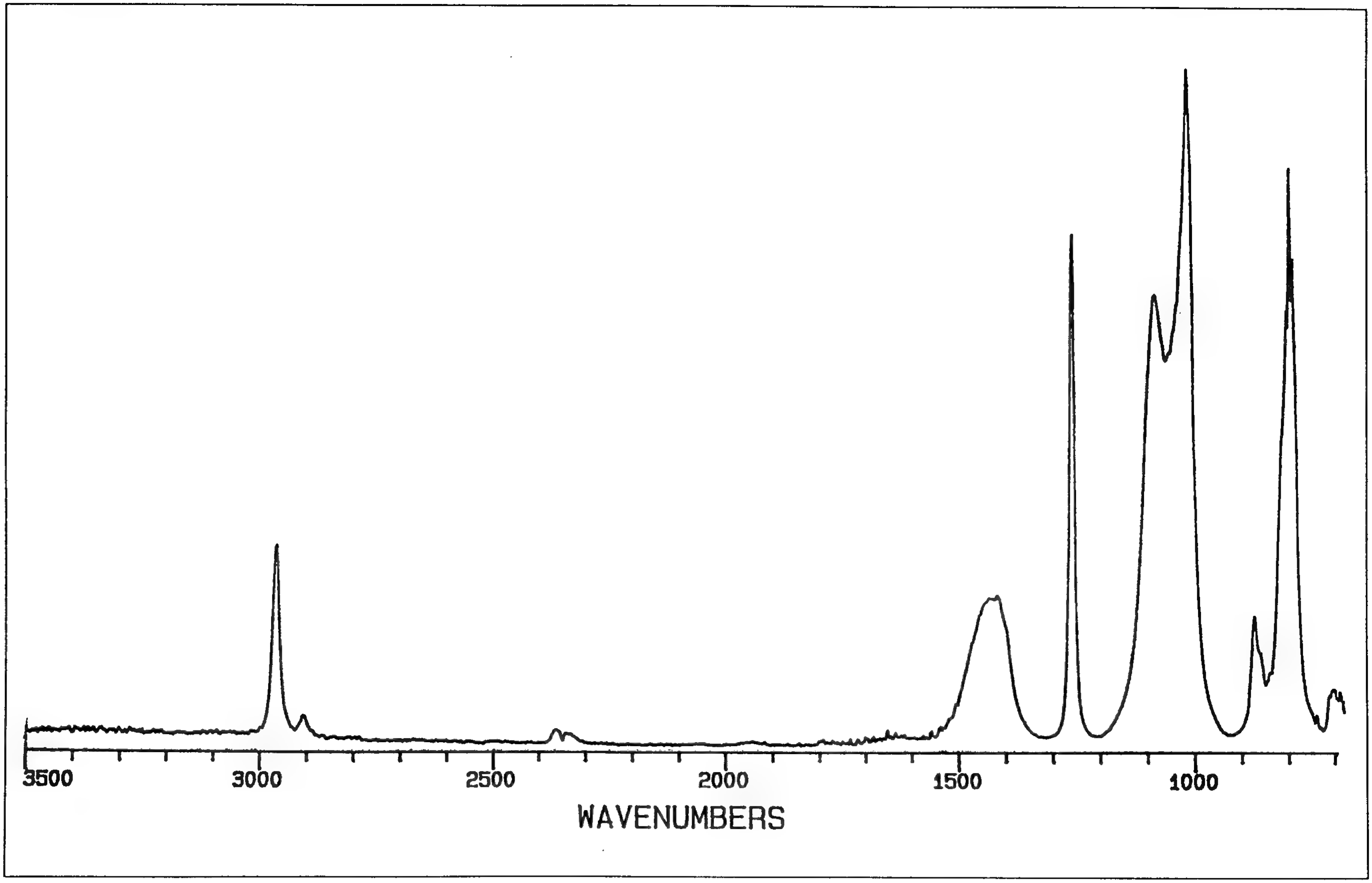


Figure 41. FTIR-ATR spectra of Dow Corning 890SL

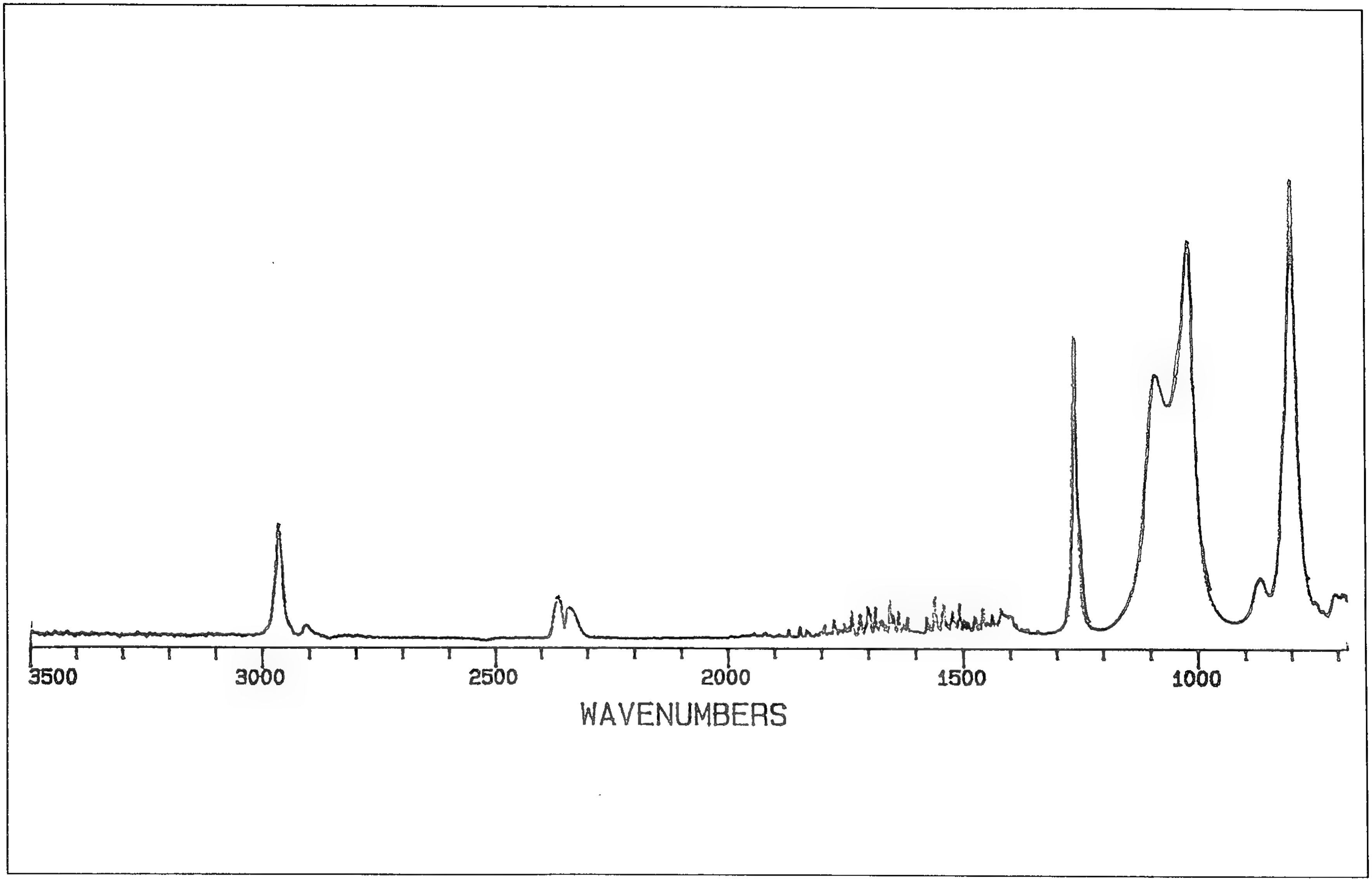


Figure 42. FTIR-ATR spectra of Dow Corning 888

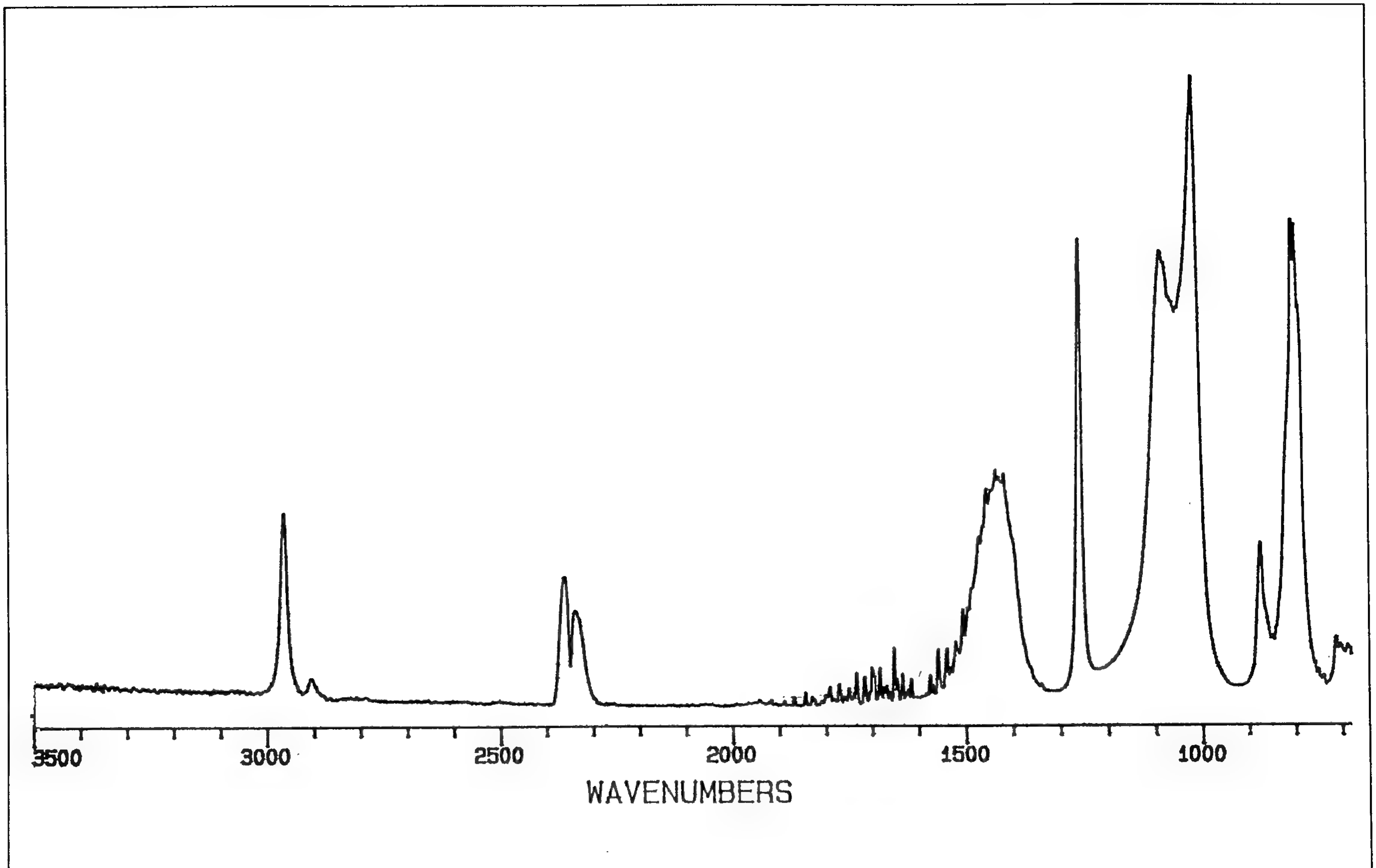


Figure 43. FTIR-ATR spectra of Dow Corning 9-1224

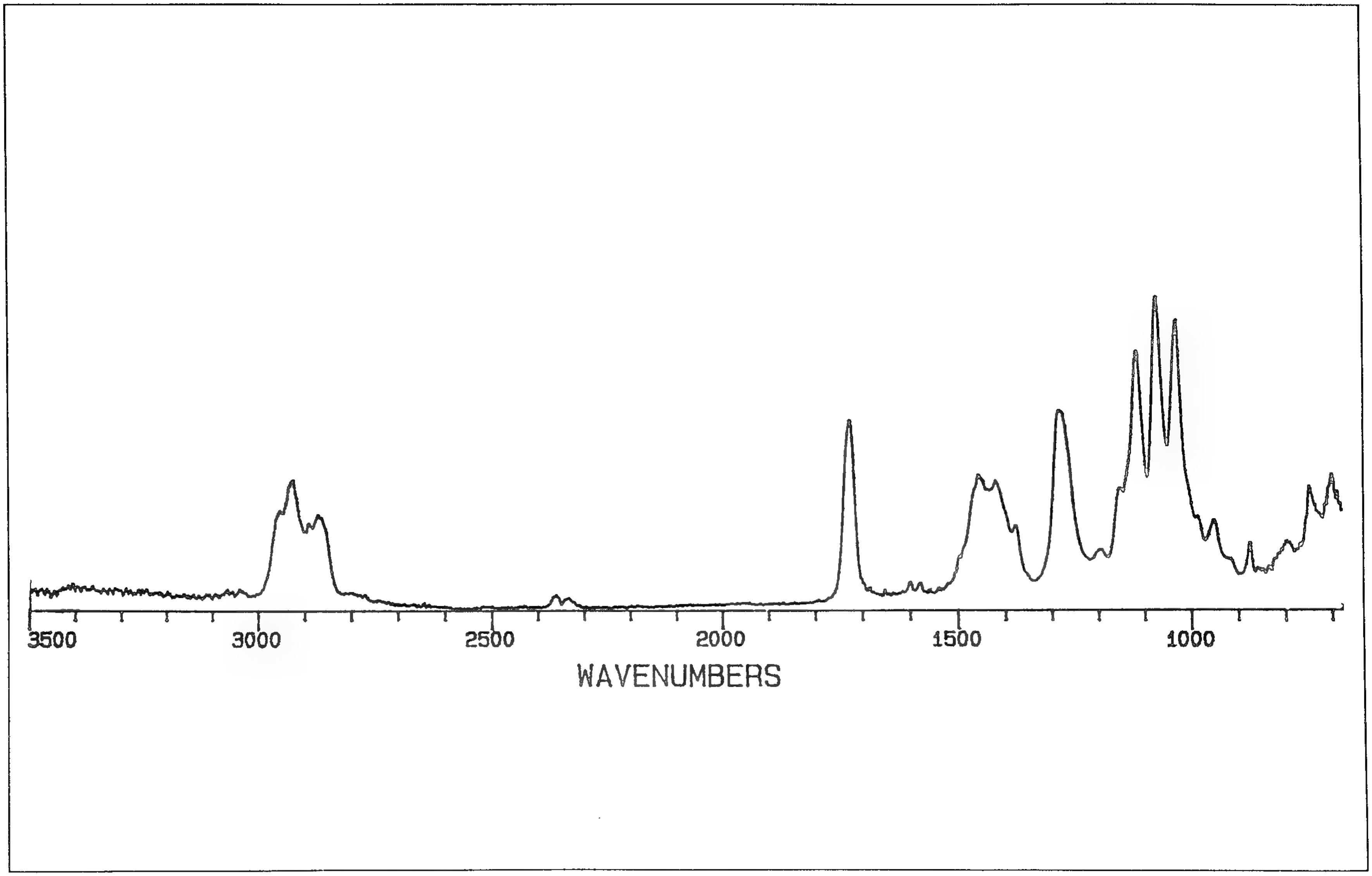


Figure 44. FTIR-ATR spectra of Koch Materials Product 9050-SL

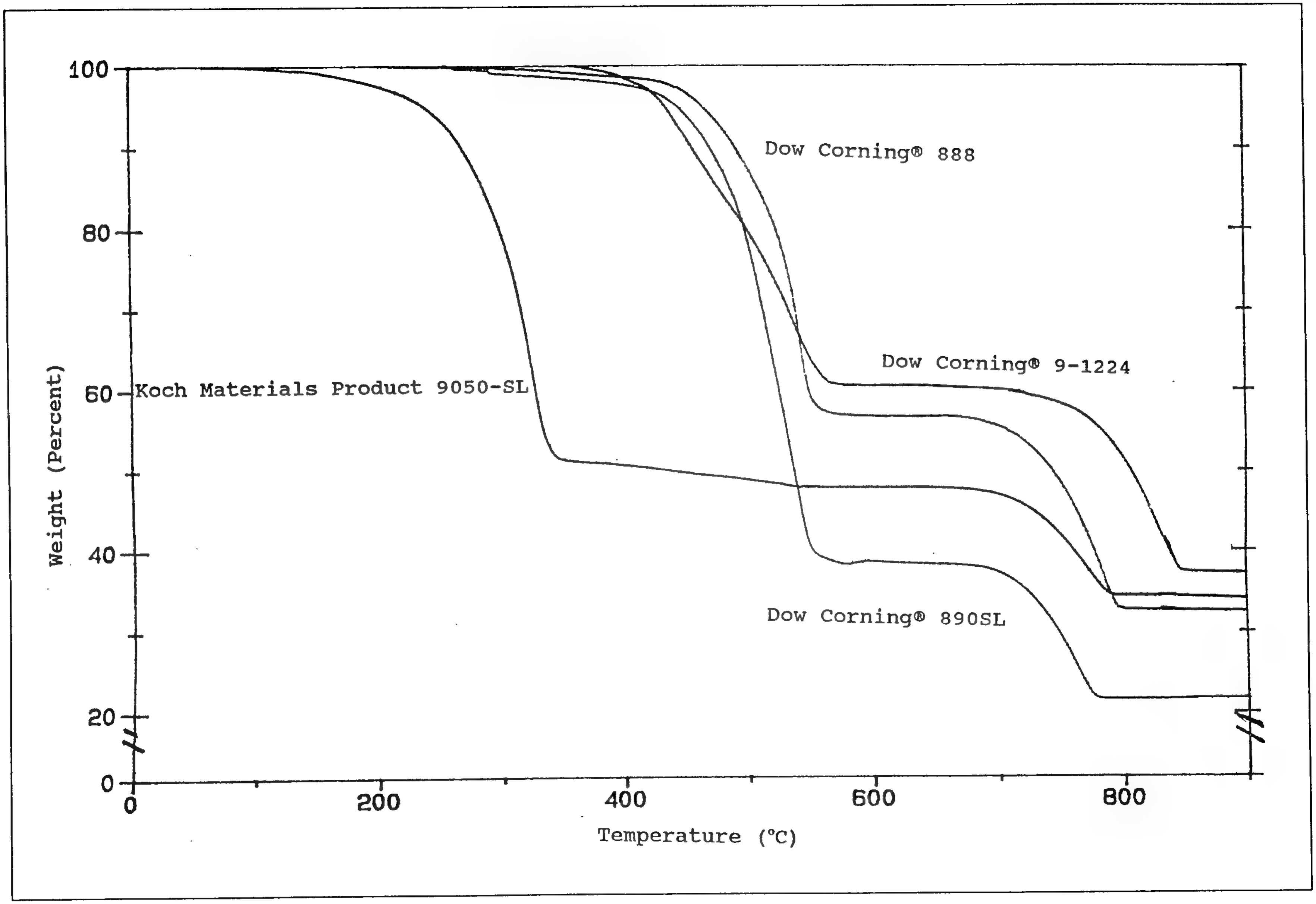


Figure 45. Thermogravimetric thermograms of sealant materials

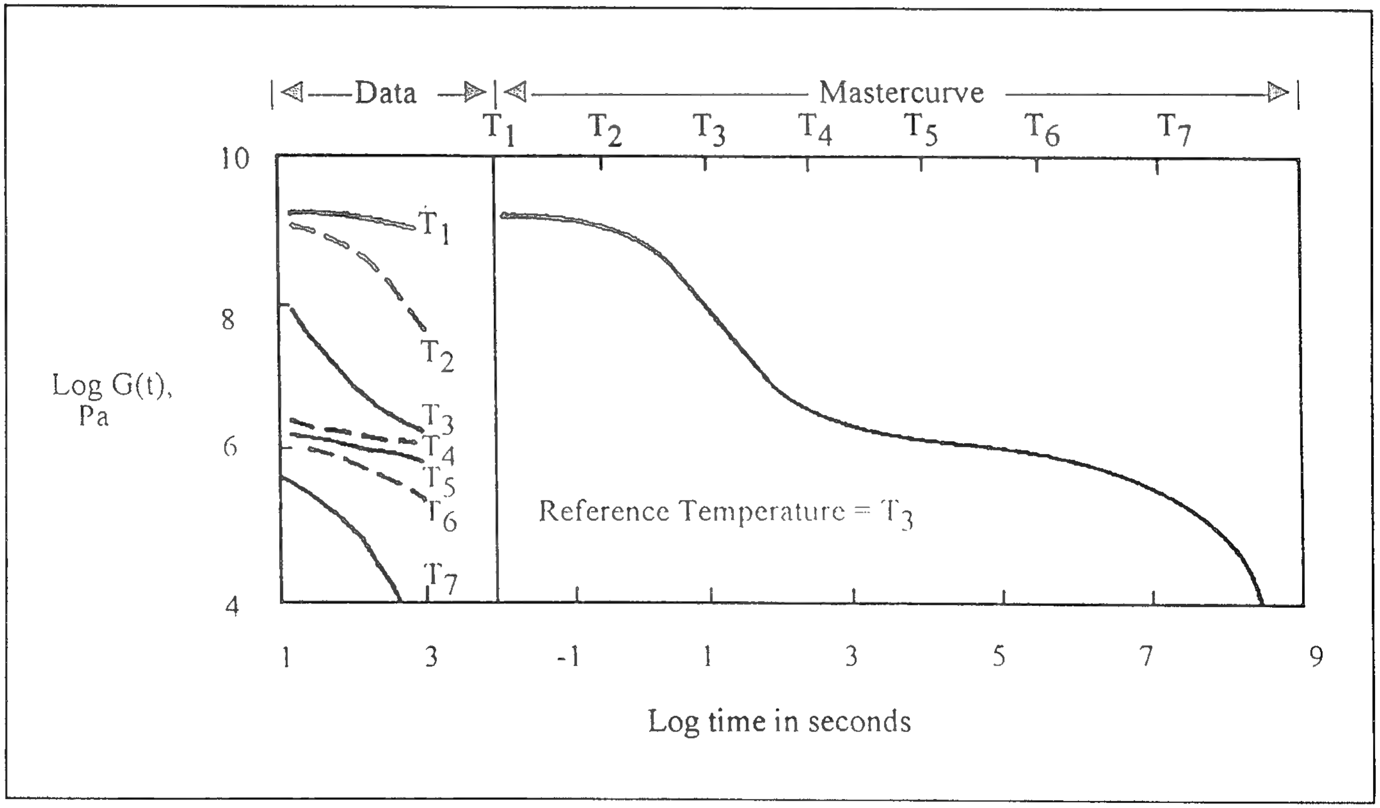


Figure 46. Mastercurve developed using time-temperature superposition

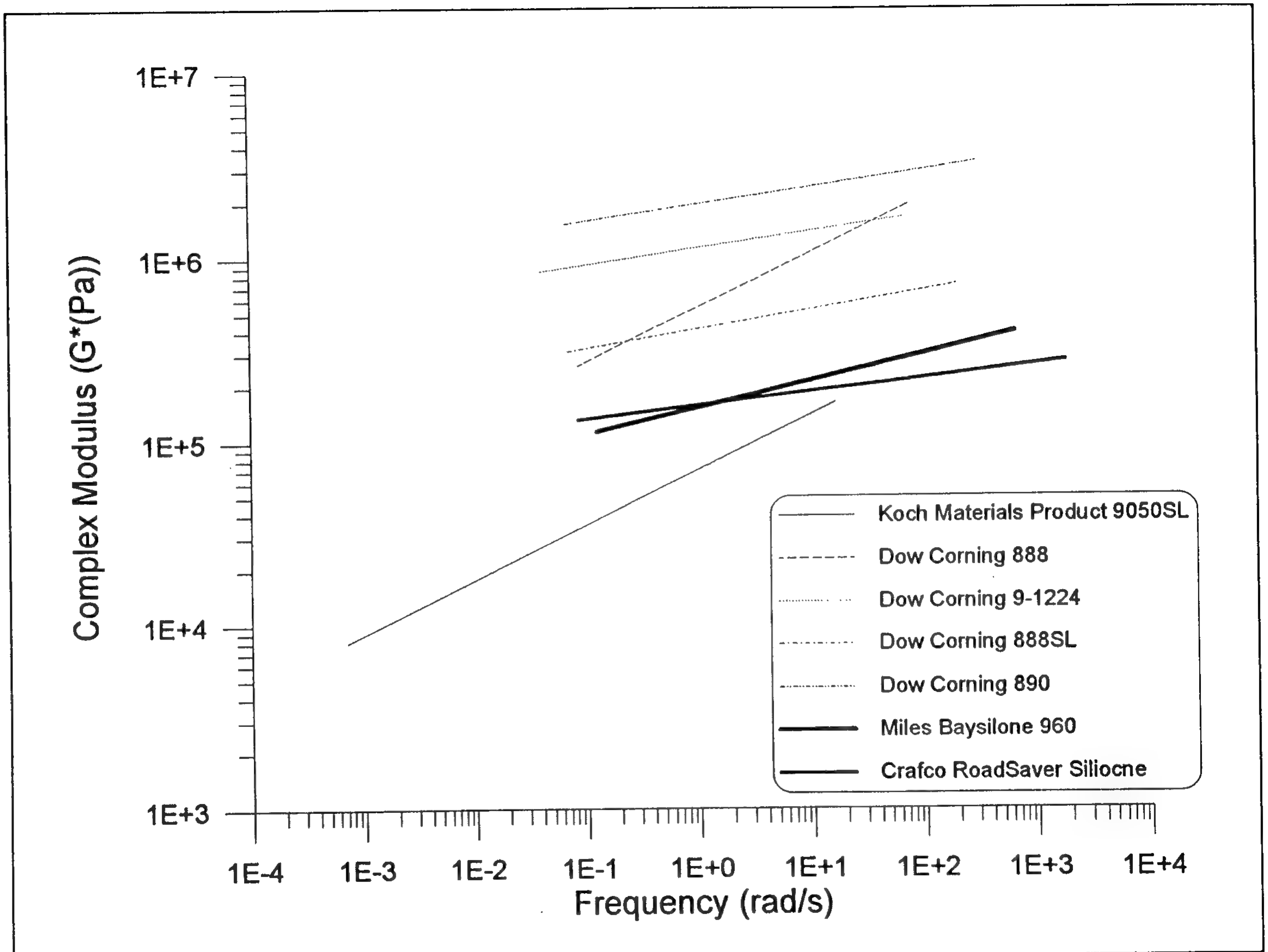


Figure 47. Mastercurve data for silicone sealants

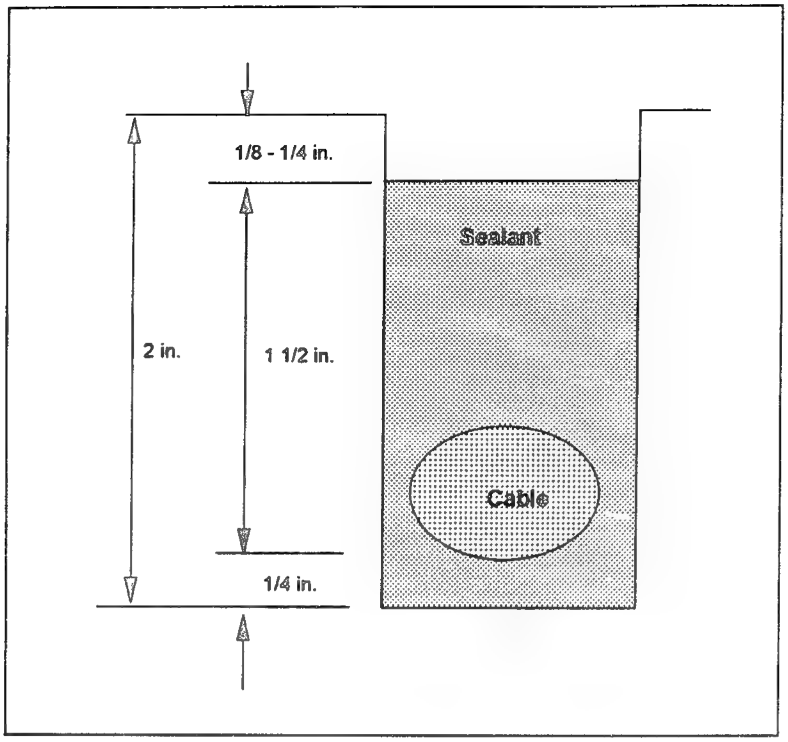


Figure 48. Standard cable-sealant (CS) configuration

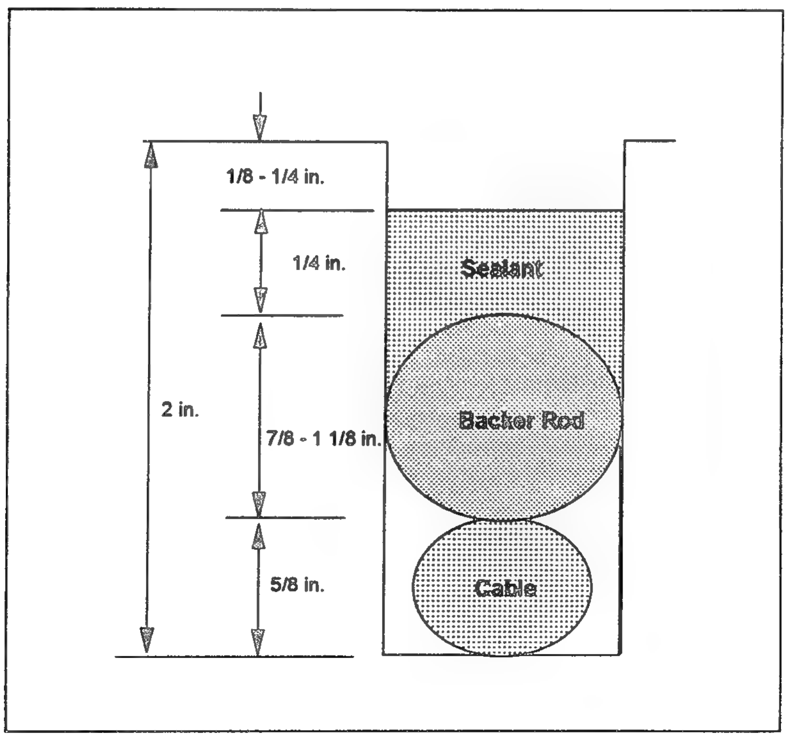


Figure 49. Proposed sealant-cable-backer rod (SCB) configuration

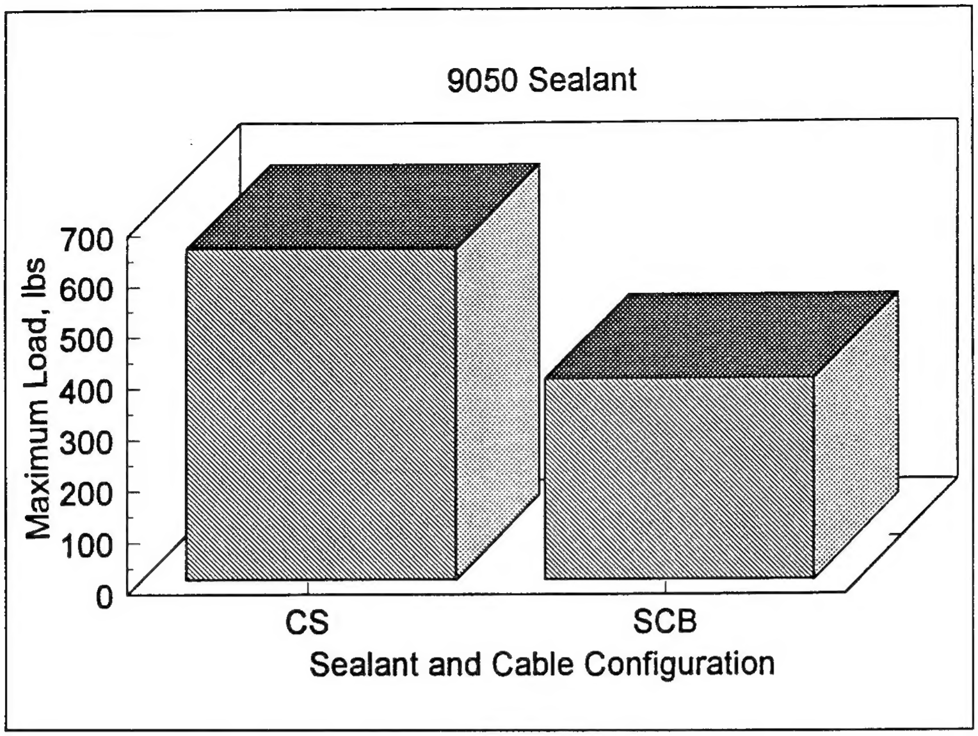


Figure 50. Koch 9050 Sealant buckling test results

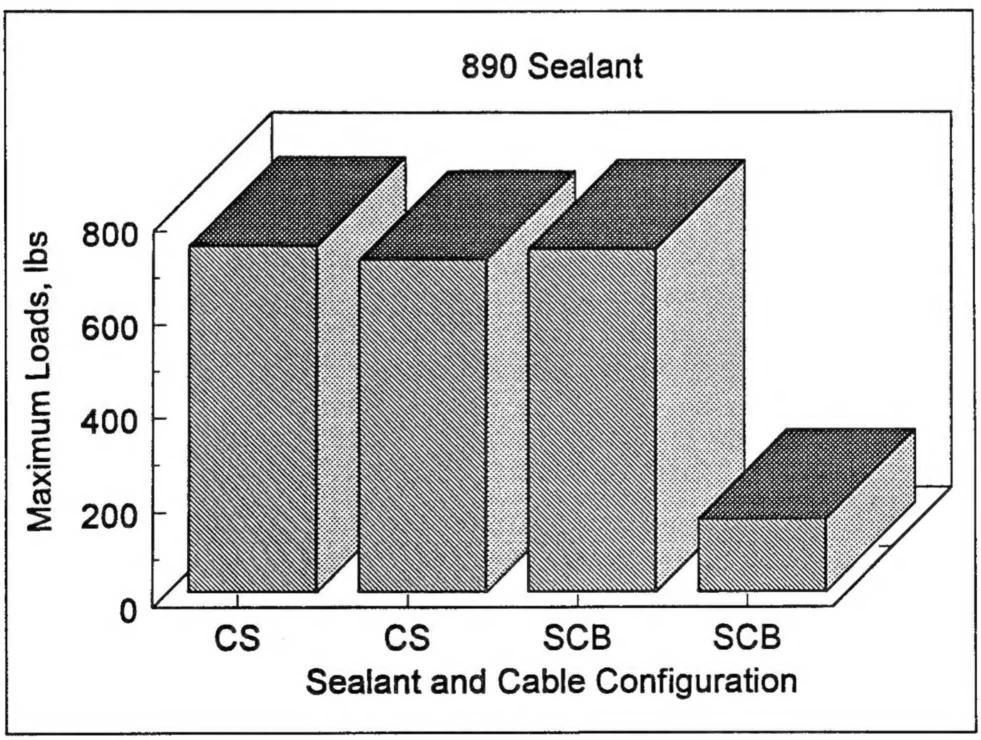


Figure 51. Dow Corning 890 buckling test results

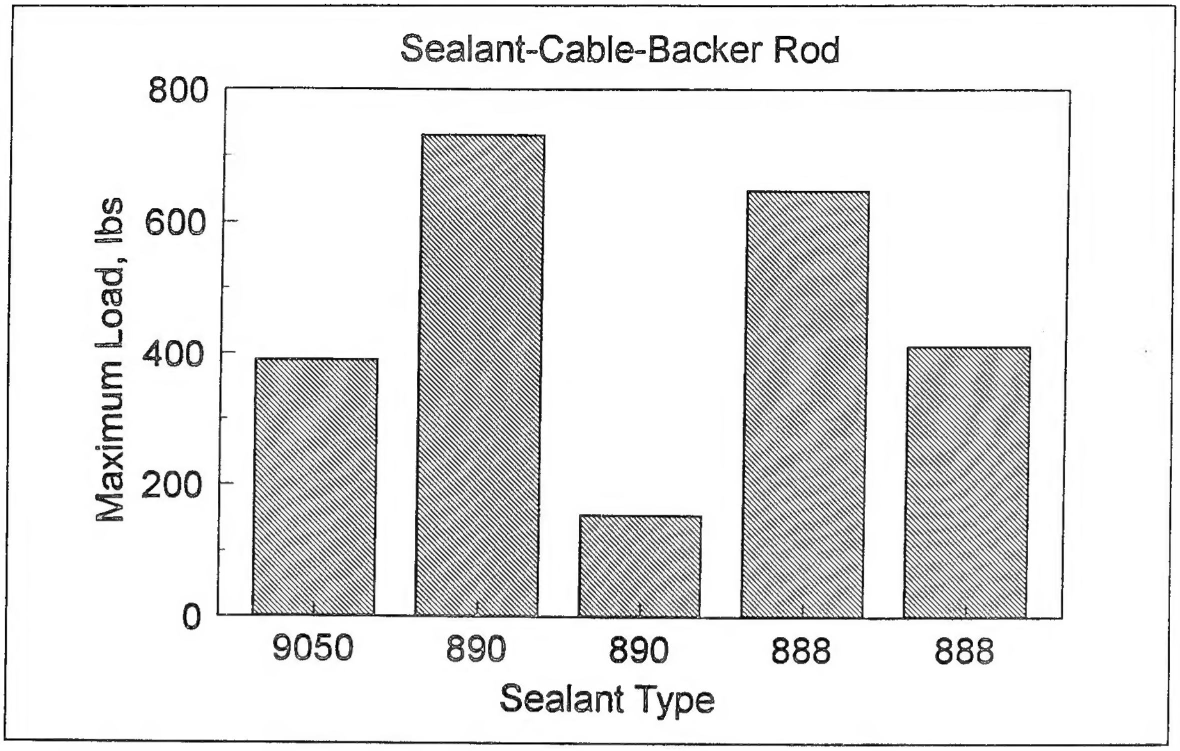


Figure 52. Sealant-cable-backer rod configuration buckling test results

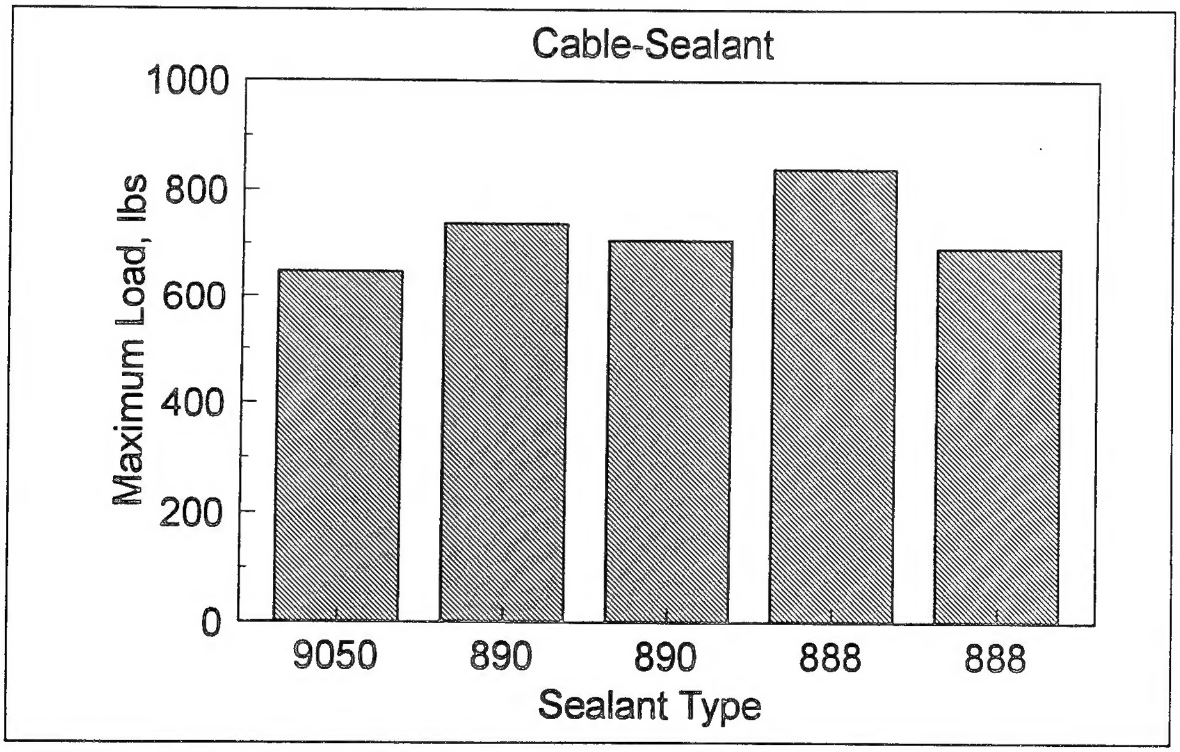


Figure 53. Cable sealant configuration buckling results

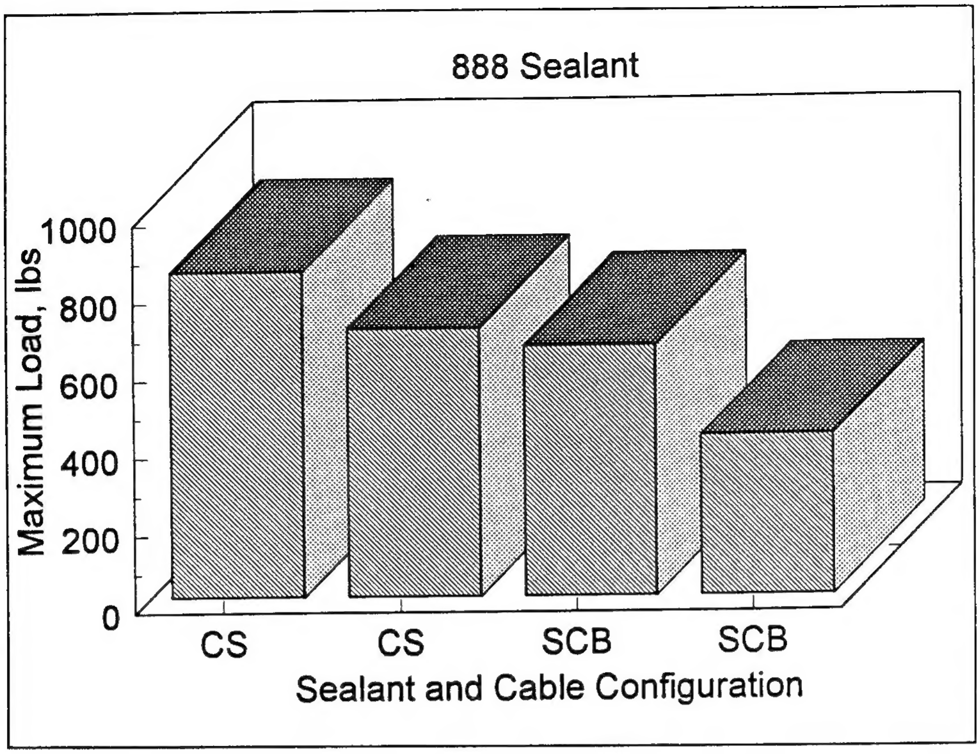


Figure 54. Dow Corning 888 buckling results

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13. ABSTRACT *(Maximum 200 words)*
Two research studies were conducted by the U.S. Army Engineer Waterways Experiment Station, both related to eaky coaxial cable sensors. In one study, the newly developed TR1 sensor cable was tested and evaluated. Basic performance characteristics of the TR1 cable were determined including detection field width/heigth and invalid alarm rate. In the other study, alternate sealant materials and a revised slot/sealant configuration were evaluated for sensor cable installation in pavement. The sealant evaluation indicated that the Will-Seal 150 and all of the silicone materials evaluated in this study were technically satisfactory for cable installation. The revised slot/sealant configuration also appeared to have no adverse effect on the sensor cable deployment.

14. SUBJECT TERMS
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Invalid alarm rate — Sealants

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